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Title: Scientific and Historic Impacts from the Manhattan Project

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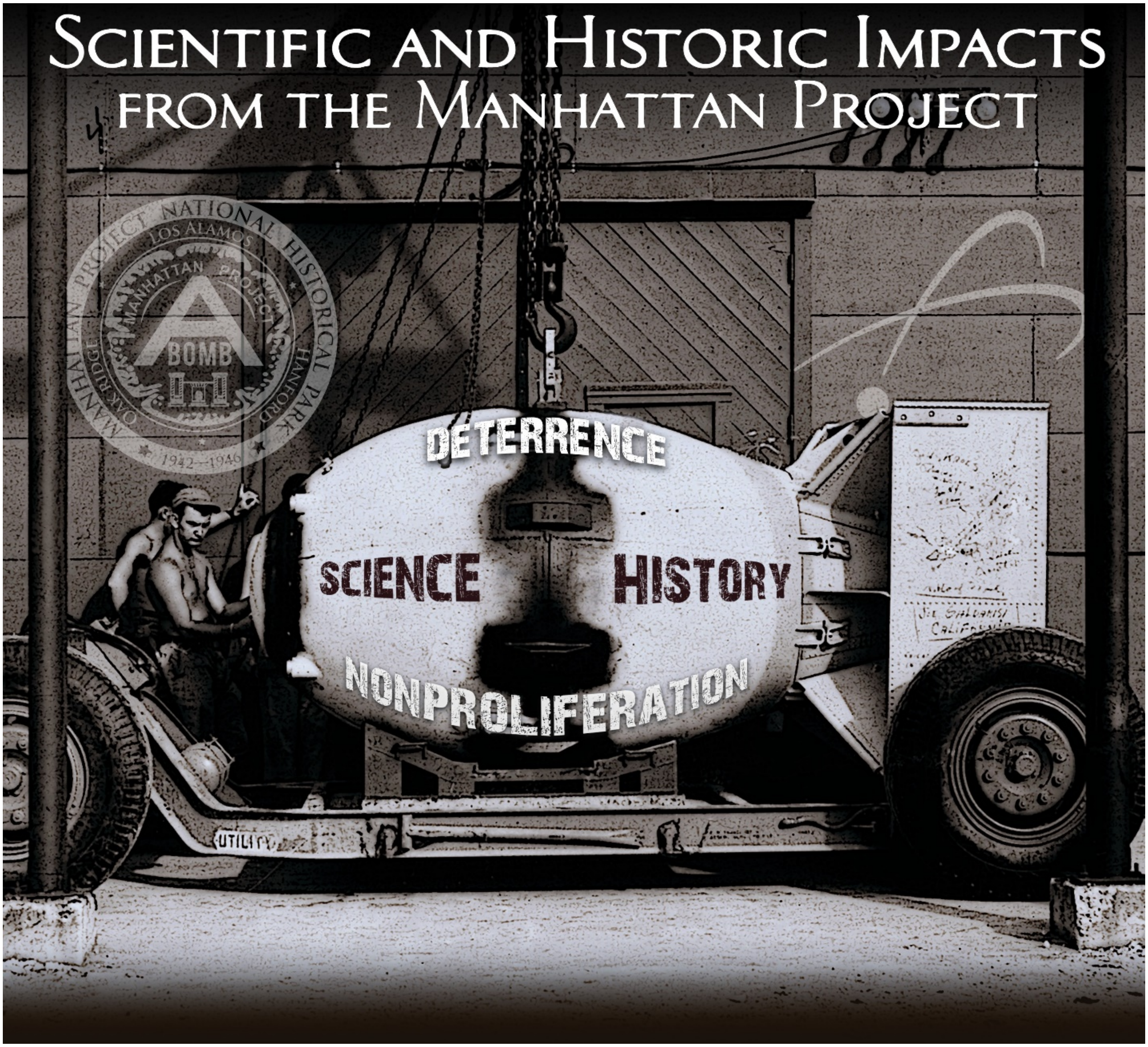

Scientific and Historic Impacts from the Manhattan Project: A Student Symposium of the History, Technology, Science, and Security Implications of the Manhattan Project

Wednesday, July 17th, 2019
8:00-4:30pm, National Security Sciences Building (NSSB) Auditorium
Los Alamos National Laboratory, Los Alamos, New Mexico
ims.lanl.gov, LA-UR-19-29157 version 2

Support for this symposium provided by: Institute for Materials Science and National Security Education Center

IMS
Institute for
Materials
Science
Los Alamos

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Introduction

Alexander Balatsky, University of Connecticut/Nordic Institute for Theoretical Physics

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The Manhattan Project (MP) was the international project that led to production of the first nuclear weapons. It opened up a new chapter in human history that we now call the atomic age, (https://en.wikipedia.org/wiki/Manhattan_Project). The MP is an example of living history where multiple generations continue to learn and evaluate the full magnitude of its history, science, technology, and deterrence and security implications throughout time.

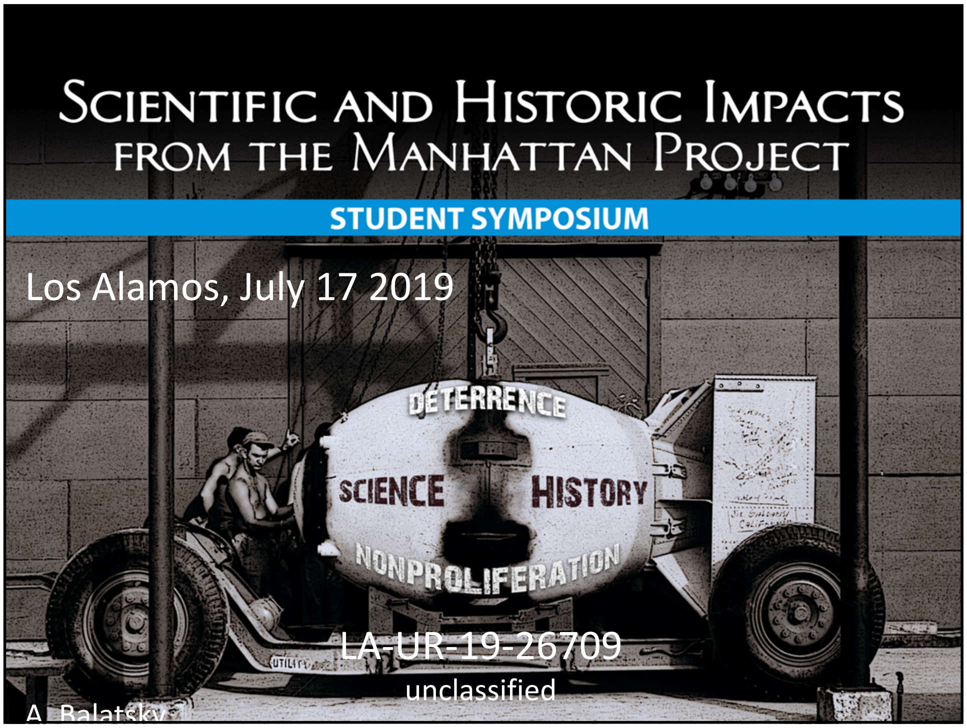
The idea to have a student symposium about the MP grew out of conversations with colleagues and students. The prevailing opinion was indeed that there is a growing interest in history, science, politics, and security implications of the MP. We thought it would be useful to keep the direct dialog and discussion going to allow younger generations the chance to formulate their own opinion.

The scope of the symposium is large, covers multiple topics, and is impossible to cover in detail in one day. We are trying to embrace a very wide spectrum of questions. The world around us is evolving and it is important to present, as completely as possible, an arc of facts about the MP and what followed. Hence, we have presentations covering the MP and broad issues of the nuclear age from the initial stages of the MP in 1942 to modern day. I believe it is important to have a forum that enables better appreciation and understanding of the MP among younger generations. Our hope is that this symposium will strengthen the ongoing dialog and create an open student forum to hear and learn about the MP.

We have assembled an excellent team of experts who can speak with authority on the topics. Senior Los Alamos National Laboratory Historian, A. Carr, will present the history of the MP. Former Los Alamos National Laboratory Director, Professor S. Hecker, will discuss the role of Pu as a key material in the MP. Los Alamos National Laboratory Fellows, Dr. M. Chadwick, Dr. D. Clark, and Dr. J. Smith, will discuss the interdisciplinary science of the MP: metallurgy, materials science, chemistry, and particle physics. Dr. G. Balatsky and P. Staples will outline the challenges of nonproliferation in the post-cold war era. We also called for a round-table discussion, moderated by Dr. J. Martz, at the end of the day. The round-table will focus on key questions and open up a discussion.

Los Alamos played a pivotal role in the MP. It is fitting therefore that the symposium on **Scientific and Historic Impacts from the Manhattan Project** will be held at Los Alamos. I am confident that this symposium presents a new opportunity for Los Alamos to educate and inform students about the historical and modern day of the nuclear age.

This book contains all the slides presented during this symposium prefaced by an extended abstract from each speaker, which enable the reader to follow the slides. An electronic copy of this book can be found at ims.lanl.gov.

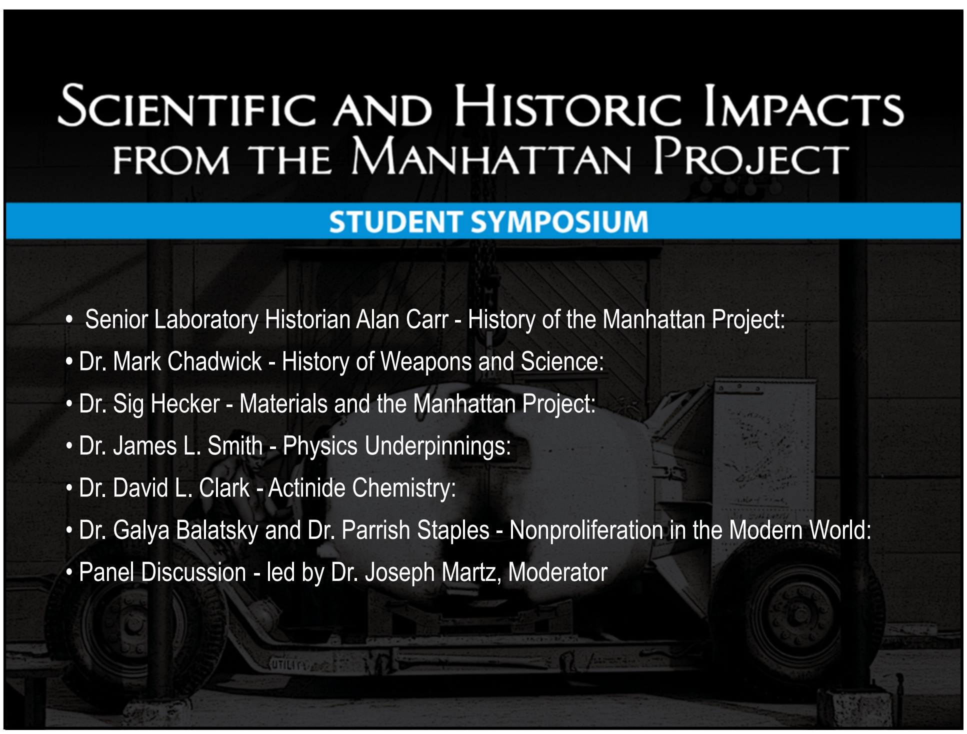


Scientific and Historic Impacts from the Manhattan Project

- **What is it**: Manhattan Project (MP) is an example of Living History
- **Why**: student interest in science of MP.
- **How**: Symposium to present the evolution of MP. Balanced discussion, open format
- Aspects: Science, technology, materials, policy, nonproliferation
- Views from different generations

Scientific and Historic Impacts from the Manhattan Project

- Two questions:
  - What was done
  - Where the history and views are going – try to predict the future.
- Learn, discuss, capture the current thinking
- Aim to have an IMS lecture notes, summarizing these discussions



Housekeeping

- Questions: clear questions at the end of presentation
- Agreements and disagreements are fine: respectful debate
- Round table discussion at 15:30 (Dr. Martz) – prepare your points
- **Acknowledge:** Efforts to organize this symposium: K. Shea (IMS administrator), F. Ronning (IMS Director), D. Clark (NSEC Director), D. Montoya (graphics), colleagues and friends.

MANHATTAN: The View from Los Alamos of History's Most Secret Project

Senior Laboratory Historian Alan Carr

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World War II, history's deadliest conflict, claimed between 60 and 80 million lives worldwide. Months before the war started, scientists first produced fission in Nazi Germany. Though scientists recognized this new process could be harnessed in the form of a weapon, it took years for policymakers in the United States to recognize nuclear weapons were both a feasible and transformative new technology that was within reach. In response, the Manhattan Project came into existence in the summer of 1942 to build reliable nuclear weapons as quickly as possible. At the center of the project was a relatively small facility in Northern New Mexico tasked with designing, building, testing and helping deliver America's nuclear weapons in combat. During the war, this secret laboratory was only known by its codenames: Project Y, Site Y and The Zia Project. Today, it is recognized around the world as Los Alamos National Laboratory: this paper presents the view from Los Alamos of history's most secret project.

On September 1, 1939 the German Army invaded Poland from the west to start World War II. On September 17th, the Soviet Union's Red Army invaded Poland from the east. A week earlier, the two nations had signed a non-aggression pact including a secret protocol which divided Poland between the two. France and Britain immediately declared war on Hitler's Germany, but reluctantly maintained neutrality with Stalin's Soviet Union. In the coming months, Stalin invaded Finland and forcefully annexed Latvia, Lithuania, Estonia and large tracts of Romania. Hitler meanwhile successfully invaded Denmark, Holland, Belgium, Luxembourg and France. After failing to force a British surrender during the Battle of Britain, Hitler turned eastward believing Britain no longer posed a strategic threat. The morning of June 22, 1941 Hitler broke the non-aggression pact with Stalin and invaded the Soviet Union: known as Operation Barbarossa, it would prove to be history's largest military campaign. Despite suffering millions of casualties in the opening months of Barbarossa, the Soviet Union was able to survive. Nonetheless, the

German Army advanced to the gates of Moscow by December 1941 where it was finally halted by exhaustion, freezing temperatures and a ferocious Soviet counterattack.

As the Soviets defended their capital, the Imperial Japanese Navy invaded the Philippines and launched a surprise attack against the United States Pacific Fleet at Pearl Harbor. Months earlier, in response to Japan's brutal occupation of Southeast Asia, the US imposed significant sanctions on Japan, including the embargo of resources crucial to the war effort such as crude oil and scrap metal. Rather than curbing aggression, the Japanese conceived the plan for the attack on Pearl Harbor. It was hoped the strike would yield a quick and decisive victory over the United States, which was still reeling from the Great Depression. But on the contrary, this attack would rejuvenate the US economy and, after years of fighting, result in the complete annihilation of Imperial Japan.

Months before the war started, German scientists produced fission. At that time, no country was better poised to turn this process into a bomb than Nazi Germany. In addition to having some of the world's greatest scientists, Germany also had a tradition of excellent engineering, significant manufacturing capabilities and direct access to uranium ore. But, as was the case in the United States, the German government did not recognize the transformative nature of nuclear weapons. It is well-known that Albert Einstein, at the urging of Hungarian-born physicist Leo Szilard, wrote a letter to President Roosevelt warning him of Germany's nuclear potential. However, Einstein and Szilard described the potential weapon as such: "A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory." More than 20 years earlier, an ammunition ship exploded in the port of Halifax, Canada, destroying *the whole port together with some of the surrounding territory*. Because Einstein and Szilard had described an accident, not a transformative weapon, American research in the years that followed would focus on producing reactors for electricity rather than nuclear weapons.

Weeks before the Battle of France began two Axis-born physicists, Otto Frisch (Austria) and Rudolf Peierls (Germany) working at the University of Birmingham penned a letter to the British Government describing a practical design for a nuclear weapon that could be delivered by air. Willing to pursue a decisive weapon that might turn the tide of the war, the government sponsored a feasibility study to further explore the Frisch-Peierls concept. Days after the German invasion of the Soviet Union the study, known as the MAUD Committee Report, was completed. It confirmed the Frisch-Peierls proposal: transformative, air-deliverable nuclear weapons were most likely only a few years away.

Britain now had an ally of convenience in the Soviet Union courtesy of the German invasion, however most agreed the Soviet Union would wither quickly amidst the German onslaught. Britain had hoped to bring the United States into the war since its onset, but to no avail. As the Germans pushed deep into the Soviet Union, the British Government sent a special mission to the US armed with a copy of the MAUD Committee Report. British leaders hoped to show the Americans nuclear weapons were at-hand, raising the inevitable question: *how close might the Germans be to perfecting a nuclear bomb?* Unfortunately, for many months the MAUD Committee Report was ignored in the US, until senior scientific advisors recognized its significance in the days leading-up to Pearl Harbor. Just as officials began thinking about a fission weapon in more serious terms, the Japanese attack and the subsequent German declaration of war on the United States created a new set of priorities. Still, as the early months of 1942 passed, the question of a German nuclear monopoly remained.

Finally, in the summer of 1942, the Manhattan Project was born. The small committees and offices that had overseen the government's nuclear research were largely replaced by the Army Corps of Engineers. The Army set-up the initial headquarters in Manhattan, hence the project's iconic name. Colonel Leslie Groves, a highly-educated and experienced engineer who had built the Pentagon in approximately 18 months, was selected to lead the project. In addition to a promotion to General, Groves was given the highest priority for labor and war materials, as well as an unlimited budget. He was also introduced to a man many considered to be America's leading theoretical physicist: J. Robert Oppenheimer.

At the peak of the Manhattan Project, General Groves employed nearly 130,000 employees simultaneously at sites all over the country. The three main installations included Oak Ridge, Tennessee; where uranium would be enriched; and Hanford, Washington; which would produce plutonium. Oppenheimer, who had thoroughly impressed Groves, was selected to lead the third site: the project's weapons design laboratory. As the Germans besieged Stalingrad, Manhattan Project officials searched for a suitable location: the laboratory had to be remote, far inland, near a rail line and the land would have to be easy to acquire. New Mexico, a place Oppenheimer knew well, seemed ideal. An area known as Los Alamos (Spanish for *the trees*) was selected late in 1942 and its inhabitants, the students and staff of a school for boys and several local homesteaders, were promptly evicted. In the early months of 1943, the Laboratory and a small, adjoining community were constructed. In April the first, major technical conference (The Los Alamos Primer Conference) was held to baseline the staff's knowledge of nuclear science. Later that month, the University of California signed a contract to operate the Laboratory on behalf of the Army, lending its illustrious name to the Manhattan Project in the national interest during a time of war. This gave Oppenheimer a powerful recruiting tool, in that he could offer prospective staff members employment with the University.

Back on December 2, 1942, Italian Nobel Laureate Enrico Fermi's team at the University of Chicago initiated the world's first controlled nuclear chain reaction. Arguably history's most significant individual scientific experiment, the chain reaction confirmed nuclear weapons were possible: if one can produce a controlled chain reaction, one can produce an uncontrolled chain reaction (i.e., a bomb). Encouraged by Fermi's success at Chicago, work progressed quickly at Los Alamos throughout 1943. The main bomb design, codenamed Thin Man, was a gun-assembled plutonium device. Another gun-assembled weapon, called Little Boy, was developed concurrently with Thin Man. In a gun-assembled weapon, a fissile projectile is fired at a fissile target to achieve supercriticality. Thin Man was the preferred design because it used plutonium, a more energetic material that could be produced far more easily than enriched uranium. Unfortunately, in the spring of 1944, Project Y suffered a major setback when future Nobel Laureate Emilio Segre discovered plutonium would not work in a gun-assembled device: an overabundance of neutrons would cause the device to pre-initiate before it fully assembled, resulting in a non-nuclear fizzle.

In response, Oppenheimer reorganized the Laboratory to construct an imploding plutonium bomb dubbed Fat Man. In Fat Man, thousands of pounds of high explosives (HE) would be used to compress a sphere of plutonium to achieve supercriticality. If Fat Man worked, the payoff would be immense: the weapon would be very efficient and, unlike Little Boy, it could be rapidly reproduced. But it was late in the war, no one knew how close the Germans might be to producing a nuclear bomb, Fat Man was relatively complicated and it relied entirely on high explosives; a material designed to expand, not implode. As scientists at the Laboratory developed methods to assess implosion tests, Oppenheimer directed Kenneth Bainbridge to prepare for a full-scale test of a Fat Man "Gadget."

There would be no full-scale test of Little Boy. Every component of Little Boy was rigorously tested at Los Alamos and, based on those test results, Laboratory scientists were certain the bomb would function in combat. As implosion testing proceeded, the staff grew increasingly confident that Fat Man would also work, but that confidence never translated into certainty. As such, the world's first nuclear weapons test was performed the morning of July 16, 1945. Dubbed Trinity by Oppenheimer, the test produced a yield equivalent to 21,000 tons of TNT and opened a new era in human history: the Nuclear Age.

Nazi Germany collapsed in May 1945, just over two months prior to Trinity. The cost of achieving victory was enormous: during World War II over 300 Americans died in combat, on average, each day. The price was far higher for the Soviet Union, considering 15,000 to 20,000 died on a daily basis due to military action. A vast majority of American and British resources had gone to Europe to help defeat Germany, yet the Allies were able to rout the Japanese in battle after battle with only a small fraction of total resources. Japan had no path to victory, yet continued to fight for several reasons. For instance, in Japan it was considered culturally unthinkable to surrender. Japan lost several battles in World War II, but the country had never lost a war. Although Japanese leaders knew the war was lost, they fought on hoping to extract more favorable terms by inflicting the maximum amount of pain on the Allies. Mounting defeats, conventional bombing, an ever-contracting blockade and the public threat of "prompt and utter" destruction after Trinity had not compelled the Japanese to surrender. Before invading the Japanese home island of Kyushu, the Allies would unleash nuclear weapons against Japan, hoping they would bring an abrupt end to the war.

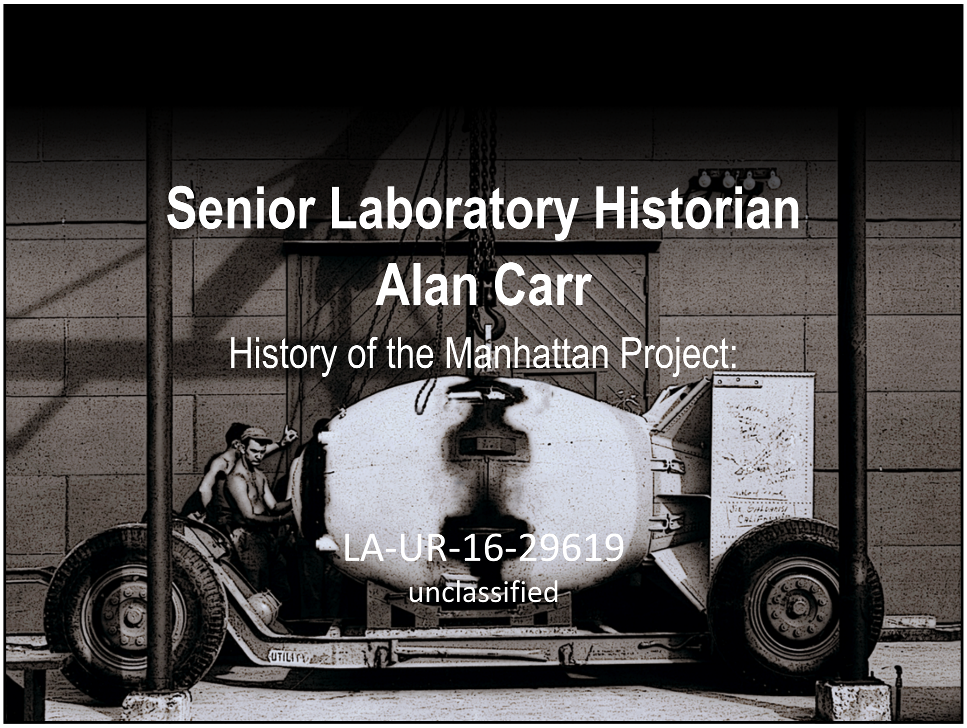
On August 6th, the B-29 bomber *Enola Gay* carried Little Boy into combat against the Japanese city of Hiroshima: the 15kt blast destroyed five square miles of the city. By the end of November 1945, 64,500 people – including thousands of Korean forced laborers and approximately ten American POWs – died as a result of the attack. Unfortunately, the Japanese did not surrender. On August 8th, the Soviet Union declared war on Japan and invaded Manchuria early the next morning, killing nearly 84,000 Japanese soldiers in the short campaign that ensued. Hours later, the B-29 *Bockscar* arrived at the city of Kokura with Fat Man armed. However, unable to visually acquire the city below due to cloud cover, the plane left after three bombing runs for the secondary target: Nagasaki. Shortly after 11:00 AM, Fat Man exploded over the Mitsubishi-Urakami Torpedo Works, the factory that manufactured torpedoes used at Pearl Harbor. Though the blast produced by Fat Man was greater than that of Little Boy (21kt vs. 15kt), fewer people died because the detonation point was on the outskirts of town. Still, just over 39,000 people – including thousands of Korean and hundreds of Chinese forced laborers – died before the year was out. A letter penned by future Nobel Laureate Luis Alvarez, with input from fellow Los Alamos scientists Phillip Morrison and Robert Serber, addressed to Japanese physicist Ryokichi Sagane was dropped near Nagasaki, several miles from ground zero. In part it read, "As scientists, we deplore the use to which a beautiful discovery has been put, but we can tell you that unless Japan surrenders at once, this rain of atomic bombs will increase manyfold in fury." It was a promise the US could have made good on: multiple Fat Man-type units could have been delivered in combat on a monthly basis from that point forward.

The next day, on August 10th, the Japanese Government informed the Allies it would surrender, provided the agreement "does not comprise any demand which prejudices the prerogatives of His Majesty [the Emperor, Hirohito] as Sovereign Ruler." In response, Secretary of State James F. Byrnes wrote:

> From the moment of surrender the authority of the Emperor and the Japanese Government to rule the state shall be subject to the Supreme Commander of the Allied Powers who will take such steps as he deems proper to effectuate the surrender terms…The ultimate form of government of Japan shall, in accordance with the Potsdam Declaration, be established by the freely expressed will of the Japanese people.

Thus Japan surrendered unconditionally and the armistice went into effect on August 14th, but not before tens of millions lay dead among the ruins of a largely destroyed world.

There was a celebration back at Los Alamos, but the excitement was tempered by fears that the next world war would feature nuclear weapons. On October 16th, General Groves awarded the Laboratory – now publicly known as Los Alamos Scientific Laboratory – the Army-Navy "E" Award for excellence in wartime production. In accepting the award on behalf of Los Alamos, Director Oppenheimer warned: "The people of this world must unite or they will perish. This war that has ravaged so much of the earth, has written these words. The atomic bomb has spelled them out for all men to understand." Although the unity Oppenheimer called for remains elusive, the threat of nuclear weapons has helped prevent another world war. Today, it remains the mission of Oppenheimer's Laboratory to develop technologies that will help make the world safer and more sustainable for its inhabitants.



Los Alamos
NATIONAL LABORATORY
EST. 1943

MANHATTAN

The View from Los Alamos of History's Most Secret Project

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Hitler *and* Stalin Start WWII

- Hitler and Stalin secretly divided Poland in August 1939
- Germany invaded Poland on September 1st
- The Soviet Union invaded Poland on September 17th
- Britain and France declared war on Germany, but maintained neutrality with the Soviets
- In November, the Stalin invaded Finland
- The Soviet Union annexed Bessarabia, Northern Bukovina, and the Hertza region of Romania in June 1940
- Latvia, Lithuania, and Estonia were forcefully annexed into the Soviet Union in August 1940

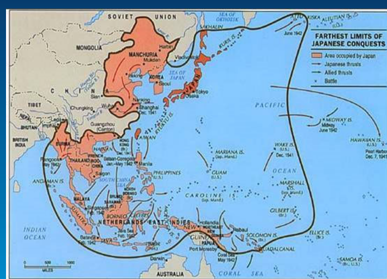
Los Alamos
NATIONAL LABORATORY
EST. 1943

German Aggression, 1940-1941

- Germany invaded Denmark and Norway in April 1940
- The following month, the Germans attacked Holland, Belgium, Luxembourg, and France
- Italy declared war on Britain and France on June 10th
- The Battle of Britain began in early August and ended in October
- In the spring of 1941, the Germans invaded the Balkans
- The Germans attacked the Soviet Union on June 22, 1941
- By late 1941, the German advance was finally halted at the gates of Moscow

War Breaks-Out in the Pacific

- On December 7, 1941, the Japanese attacked the United States Pacific Fleet at Pearl Harbor
- The United States and Britain immediately declared war on Japan
- Japan invaded the Philippines on December 8th
- On December 11th, Germany and Italy declared war on the United States
- "We won a great tactical victory at Pearl Harbor and thereby lost the war." – Admiral Hara Tadaichi




The Tribune
BATAAN COMPLETELY OCCUPIED BY JAPANESE
Japanese Forces Take Cebu

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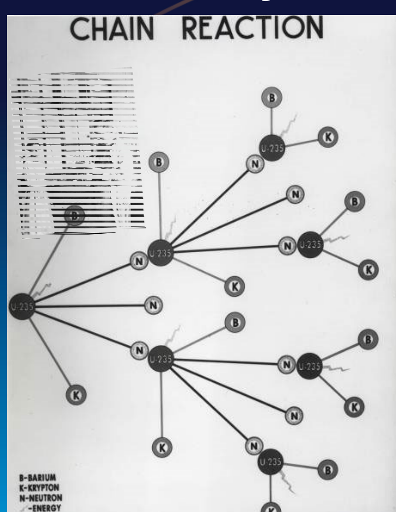
The Discovery of Fission



- In Germany, in late 1938, Fritz Strassmann and Otto Hahn produced barium by bombarding uranium with neutrons
- Lise Meitner and Otto Frisch identified this process as nuclear fission in early 1939
- Fission: The splitting of an atomic nucleus resulting in the release of large amounts of energy
- Scientists immediately realized the potential for an atomic bomb

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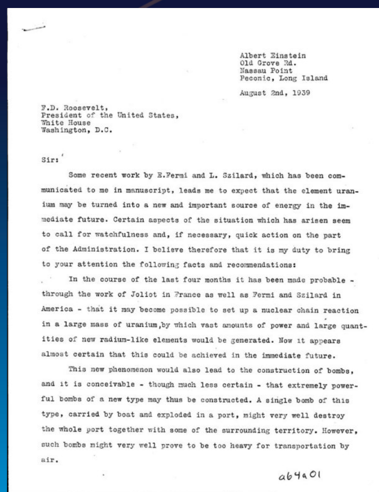
The Birth of the American Project

Los Alamos NATIONAL LABORATORY EST. 1943



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

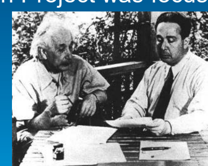
Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

a64a01

- A month before Germany invaded Poland, Albert Einstein warned President Roosevelt of fission's potential
- In October 1939, Roosevelt responded by establishing the Uranium Advisory Committee
- In the summer of 1940, it was absorbed by the National Defense Research Committee (NDRC)
- The American Project was focused project was focused on building a reactor, not a bomb



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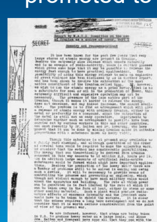
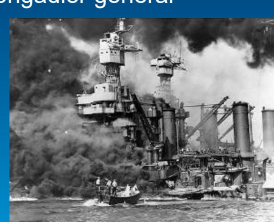
From Reactors to Bombs

Los Alamos NATIONAL LABORATORY EST. 1943

- The British MAUD report of July 1941 predicted an atomic bomb could be completed by late 1943
- In fall 1941, the NDRC chairman was given a copy of the report and bomb work accelerated
- After the Japanese attack on Pearl Harbor in December 1941 the project was turned over to the Army Corps of Engineers
- The Manhattan Engineer District was formally established in August 1942
- Colonel Leslie R. Groves was selected to lead the project in September and promoted to brigadier general





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A National Project

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The Clinton Engineer Works

- In fall 1942, a site in East Tennessee was acquired for a uranium enrichment complex
- The 59,000 acre reservation was purchased in September and construction began in early 1943
- In addition to enriching uranium, small amounts of plutonium were also produced at Oak Ridge
- In the summer of 1943, Manhattan District headquarters moved from Washington to Oak Ridge
- The Uranium 235 used in Little Boy was produced at Oak Ridge

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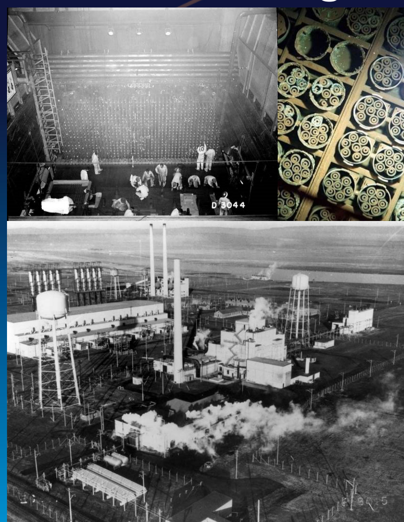
The Hanford Engineer Works



- In late 1942, the Hanford Site in Washington was selected for the plutonium production facility
- Hanford was isolated, unpopulated, and had access to abundant hydroelectric power
- The Columbia River provided the necessary 25,000+ gallons of water per-minute to cool the reactors
- Hanford's three DuPont-built reactors were based on a design by Enrico Fermi
- The plutonium used in the Trinity device and Fat Man were produced at Hanford

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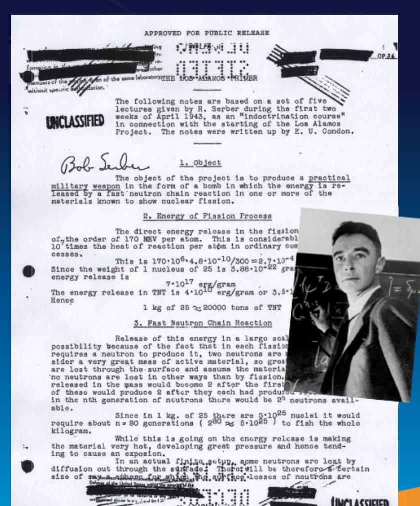
Project Y: Los Alamos

- Groves selected J. Robert Oppenheimer as director of the project's weapons design laboratory
- Oppenheimer suggested Los Alamos as a site for the lab
- The first technical conference was held in April 1943
- That same month, the University of California agreed to operate the Laboratory
- The Manhattan Project employed ~129,000 workers at its peak with the Los Alamos technical staff comprising between 1% and 2% of the work force



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THE LOS ALAMOS PRIMER

The following notes are based on a set of five lectures given by R. Serber during the first two weeks of April 1943, as an "indoctrination course" in connection with the starting of the Los Alamos Project. The notes were written up by E. U. Condon.

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Bob Serber

1. Object

The object of the project is to produce a practical military weapon in the form of a bomb in which the energy is released by a fast neutron chain reaction in one or more of the materials known to show nuclear fission.

2. Energy of Fission Process

The direct energy release in the fission of the order of 170 MEV per atom. This is considerabl 10^7 times the heat of reaction per atom in ordinary com cesses.

This is $170 \cdot 10^6 \cdot 4.8 \cdot 10^{-10}/300 = 2.7 \cdot 10^{-4}$

Since the weight of 1 nucleus of 25 is $3.88 \cdot 10^{-22}$ gra energy release is

$7 \cdot 10^{17}$ erg/gram

The energy release in TNT is $4 \cdot 10^{10}$ erg/gram or 3.5·1

Hence

1 kg of 25 $\approx$ 20000 tons of TNT

3. Fast Neutron Chain Reaction

Release of this energy in a large scal possibility because of the fact that in each fissio requires a neutron to produce it, two neutrons are sider a very great mass of active material, so grea are lost through the surface and assume the materia no neutrons are lost in other ways than by fission. released in the mass would become 2 after the first of these would produce 2 after they each had produ in the nth generation of neutrons there would be 2^n neutrons available.

Since in 1 kg. of 25 there are $5 \cdot 10^{25}$ nuclei it would require about n = 80 generations ($2^{80} \approx 5 \cdot 10^{25}$) to fish the whole kilogram.

While this is going on the energy release is making the material very hot, developing great pressure and hence tending to cause an exposion.

In an actual finite setup, some neutrons are lost by diffusion out through the surface. There will be therefore a certain size of say a sphere for which the surface losses of neutrons are

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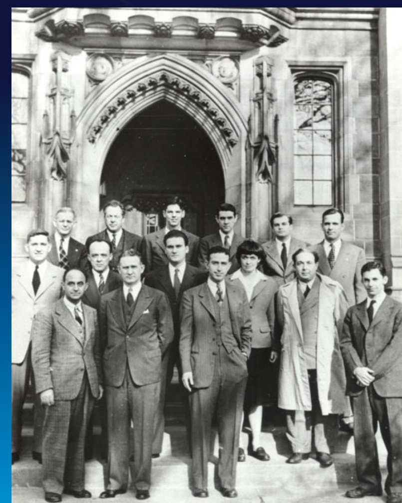
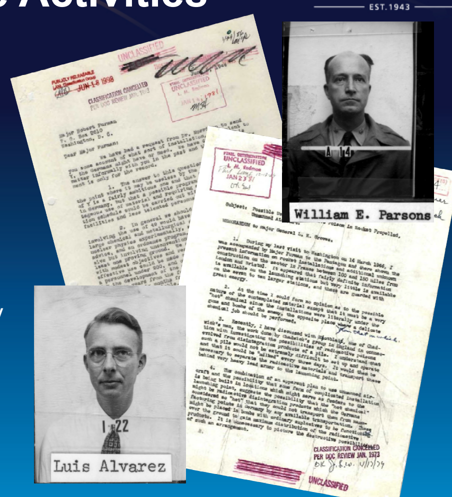
The Race for the Atomic Bomb

- There was very little information available on the progress of Axis research
- The Germans and the Japanese each had atomic bomb projects but they were only making limited progress
- On December 2, 1942 Enrico Fermi's team at the University of Chicago initiated the world's first controlled nuclear chain reaction



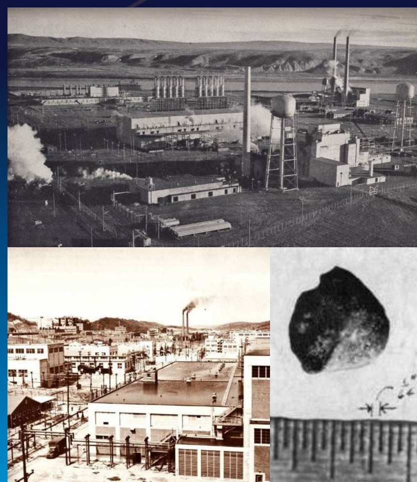
Wartime Intelligence Activities

- During the war, the Laboratory provided technical support in assessing the German nuclear weapons program
- The primary players at Los Alamos included Deak Parsons and future Nobel Laureate Luis Alvarez
- Parsons investigated the possibility of a German dirty bomb
- Alvarez estimated the minimum requirements for a German equivalent to Project Y



Subject: Possible Use of Radioactive Poison in Rocket Propelled, Unmanned Aircraft.

Building the Atomic Bombs



- Initially, scientists believed both plutonium and uranium would work in a gun-assembled device
- A gun assembly fires one piece of fissile material at another to initiate the chain reaction
- Experiments conducted at Los Alamos in the spring of 1944 demonstrated plutonium was not suitable for this type of assembly
- To salvage the plutonium production effort, a new type of assembly was pursued: implosion
- An implosion assembly compresses a core of plutonium with high explosives to initiate the chain reaction

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Project Trinity

- Scientists were confident the gun-assembled uranium weapon would work
- However, they decided it was necessary to test the more complicated implosion-assembled plutonium device, the “Gadget”
- The Manhattan Engineer District secured an area within the Alamogordo Bombing Range to test the bomb
- On May 7, 1945 one hundred tons of TNT was detonated in order to calibrate diagnostic instruments for the full-scale test to come
- The next day, May 8th, Nazi Germany formally surrendered

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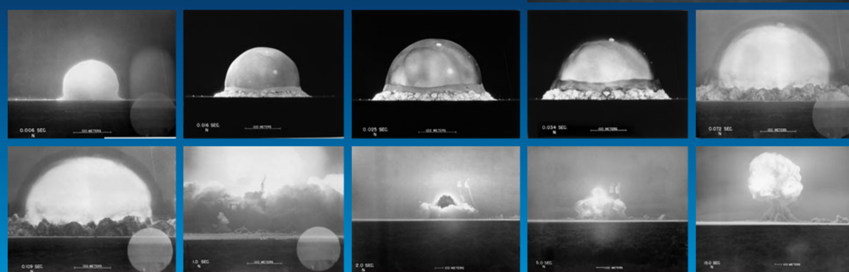
The Test…

- The world's first man-made nuclear explosion was successfully detonated July 16, 1945
- It achieved a yield of 21 kilotons (21,000 tons of TNT)



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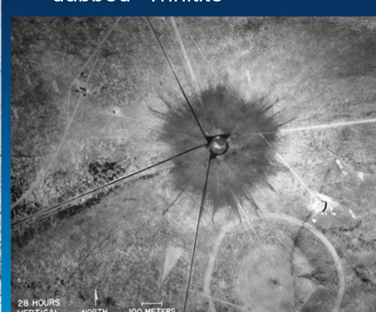
…and its Aftermath

- The blast vaporized the bomb's 100' steel tower
- The heat produced by the explosion melted the sand, forming a glass-like material dubbed "Trinitite"



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Target Selection

1. The second meeting of the Target Committee convened at 9:00 AM 10 May in Dr. Oppenheimer's office at Site Y with the following present:

DECLASSIFIED
E.O. 11652, Sec. 3(E) and 5(D) or (E)
NND 730039
By ERC NARS, Date 6-4-74

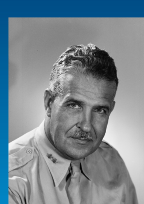
General Farrell	Dr. C. Lauritsen
Colonel Seeman	Dr. Ramsey
Captain Parsons	Dr. Dennison
Major Derry	Dr. Von Neumann
Dr. Stearns	Dr. Wilson
Dr. Tolman	Dr. Penney
Dr. Oppenheimer	

- The initial goal of the Manhattan Project had been to beat Hitler to the atomic bomb
- After Germany's collapse, the goal of the project was to end the war with Japan as quickly as possible
- A committee to select appropriate targets first met April 27, 1945
- Potential target cities included:
  - Hiroshima, Tokyo, Yokohama, Nagoya, Kobe, Kyoto, Kokura, Nagasaki, Kawasaki, Kure, Yawata, Yamaguchi, Kumamoto, Sasebo
- The Army Air Corps agreed to reserve Kyoto, Hiroshima, Yokohama, Kokura, and Niigata

Shock and Awe

- Japan never had a chance to win the war militarily
- The atomic bombings were intended to break the Japanese Government's will to resist
- Many years later, General Groves wrote in his memoir:

Admiral Purnell and I had often discussed the importance of having the second blow follow the first one quickly, so that the Japanese would not have time to recover their balance.



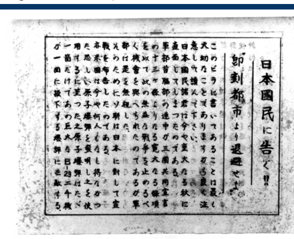
- 6 -

TOP SECRET

7. Psychological Factors in Target Selection

A. It was agreed that psychological factors in the target selection were of great importance. Two aspects of this are (1) obtaining the greatest psychological effect against Japan and (2) making the initial use sufficiently spectacular for the importance of the weapon to be internationally recognized when publicity on it is released.

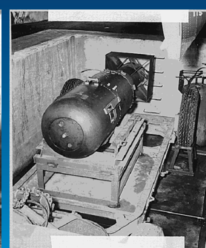
B. In this respect Kyoto has the advantage of the people being more highly intelligent and hence better able to appreciate the significance of the weapon. Hiroshima has the advantage of being such a size and with possible focusing from nearby mountains that a large fraction of the city may be destroyed. The Emperor's palace in Tokyo has a greater fame than any other target but is of least strategic value.



THOUSANDS OF THESE LEAFLETS WERE DROPPED FROM B-29'S OVER JAPAN TO WARN THAT HIROSHIMA AND OTHER CITIES MIGHT BE BOMBED TO TOTAL DESTRUCTION.

The First Strike

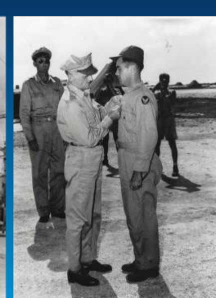
- Hiroshima, a large industrial city with an important army depot, was selected as the target
- The gun-assembled uranium weapon, nicknamed “Little Boy,” was used
- Colonel Paul Tibbets commanded the mission
- He named his plane *Enola Gay*, after his mother

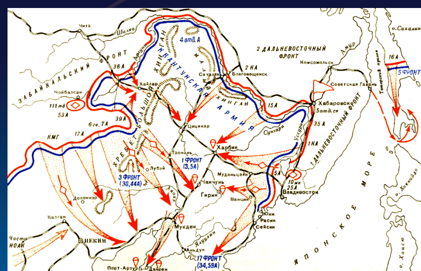

Hiroshima

- On the morning of August 6, 1945 Little Boy was dropped on Hiroshima
- The bomb achieved a yield of 15 kilotons
- 64,500 had died by mid-November 1945 according to the 1954 US Army Pathological Study
- Thousands of Koreans and at least ten American POWs died in the attack
- The strike completely destroyed five square miles of the city





Stalin Moves East



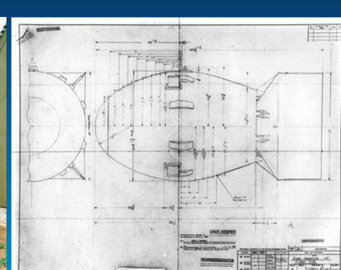
Now that the Soviet Union has entered the war against us, to continue the war under the present internal and external conditions would be only to increase needlessly the ravages of war finally to the point of endangering the very foundation of the Empire's existence.

-Hirohito, Shōwa Emperor

- Late in the evening of August 8th, the Soviet Union declared war on Japan
- The Red Army invaded Manchuria just after midnight
- The invasion was a military catastrophe for the Japanese…
- …and a diplomatic disaster as well because they had been trying to negotiate with the Allies through the Soviet Union
- Nearly 84,000 Japanese soldiers died in the campaign, which lasted approximately four weeks

The Second Strike

- Kokura, home to one of the largest arsenals in Japan, was selected as the primary target for the second mission
- Nagasaki was selected as the secondary target
- The implosion-assembled plutonium bomb, "Fat Man," was used
- The mission was flown by Major Charles Sweeny in the B-29 *Bock's Car*



Nagasaki

- Equipment problems, deteriorating weather conditions, and a delayed rendezvous between *Bock's Car* and her accompanying aircraft plagued the mission, which was carried-out on the morning of August 9th
- After three runs over Kokura, enough fuel remained for one run over Nagasaki
- The attack was successful: the bomb achieved a yield of 21 kilotons, completely destroying three square miles of the city
- 39,214 had died by mid-November 1945
- Thousands of Koreans and hundreds of Chinese died in the attack



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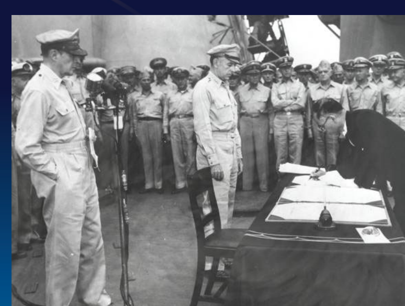
The Japanese Surrender

- On August 14th an armistice was declared
- The war officially ended on September 2nd when Japan formally surrendered aboard the USS Missouri in Tokyo Bay
- The surrender was unconditional



From the Imperial Rescript of August 14, 1945

"Despite the best that has been done by everyone—the gallant fighting of military and naval forces, the diligence and assiduity of Our servants of the State and the devoted service of Our one hundred million people, the war situation has developed not necessarily to Japan's advantage, while the general trends of the world have all turned against her interest. Moreover, the enemy has begun to employ a new and most cruel bomb, the power of which to do damage is indeed incalculable, taking the toll of many innocent lives. Should We continue to fight, it would not only result in an ultimate collapse and obliteration of the Japanese nation, but also it would lead to the total extinction of human civilization. Such being the case, how are We to save the millions of Our subjects; or to atone Ourselves before the hallowed spirits of Our Imperial Ancestors? This is the reason why We have ordered the acceptance of the provisions of the Joint Declaration of the Powers."

Hirohito, Shōwa Emperor

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The Postwar Role of the Emperor

- Hirohito was retained by the Allies and used to promote a peaceful surrender
- On August 11th, Secretary of State Byrnes had sent a telegram to the Japanese via Switzerland:

From the moment of surrender the authority of the Emperor and the Japanese Government to rule the state shall be subject to the Supreme Commander of the Allied Powers who will take such steps as he deems proper to effectuate the surrender terms…

The ultimate form of government of Japan shall, in accordance with the Potsdam Declaration, be established by the freely expressed will of the Japanese people.

The Tragedy of Statistics

American Fatalities:	418,500 (over 300 died **each day**)
Soviet Fatalities:	As many as 27,000,000
American Pearl Harbor Fatalities:	2,402
Stalingrad *Casualties*:	2,000,000
American D-Day Fatalities:	2,499
Operation Meetinghouse (Tokyo) Fatalities:	100,000
Hiroshima Fatalities:	64,500 (mid-November 1945)
Nagasaki Fatalities:	39,214 (mid-November 1945)
Jewish Holocaust Fatalities:	5,900,000
Chinese Fatalities	As many as 20,000,000

"A single death is a tragedy,
a million deaths is a statistic."

Joseph Stalin

WORLD WAR II CLAIMED BETWEEN 60 AND 80 MILLION LIVES

The New World

- On October 16, 1945 Los Alamos received the Army-Navy “E” Award for its contributions to the war effort
- Robert Oppenheimer proudly accepted the award, but also discussed the perils of the new atomic age

“It is with appreciation and gratefulness that I accept from you this scroll for the Los Alamos Laboratory, and for the men and women whose work and whose hearts have made it. It is our hope that in years to come we may look at the scroll and all that it signifies, with pride.

Today that pride must be tempered by a profound concern. If atomic bombs are to be added as new weapons to the arsenals of a warring world, or to the arsenals of the nations preparing for war, then the time will come when mankind will curse the names of Los Alamos and Hiroshima.

The people of this world must unite or they will perish. This war that has ravaged so much of the earth, has written these words. The atomic bomb has spelled them out for all men to understand. Other men have spoken them in other times, and of other wars, of other weapons. They have not prevailed. There are some misled by a false sense of human history, who hold that they will not prevail today. It is not for us to believe that. By our minds we are committed, committed to a world united, before a common peril, in law and in humanity.”

J. Robert Oppenheimer

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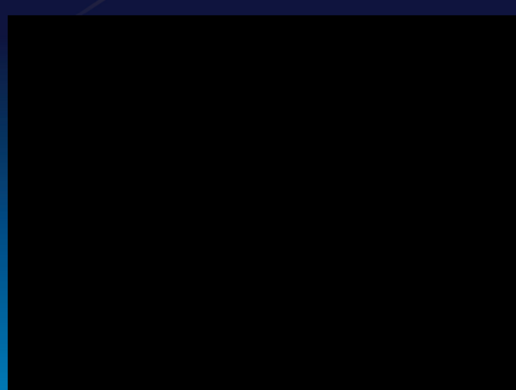
The Birthplace of Arms Control



“In contrast with almost every other field of human endeavor…the atomic bomb business seeks to put itself out of business. Our one objective at Los Alamos has always been that bombs never get used; that the United States was always ahead both in technology and a willingness to discuss the abandonment of nuclear warfare.”

Norris Bradbury

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LA-UR-28295

Top 10 Weapons Breakthroughs in Los Alamos History

Mark B. Chadwick, Los Alamos National Laboratory

1. Invention of the Atomic Bomb

The dawn of the Nuclear Age occurred on the morning of July 16, 1945, when Los Alamos conducted the Trinity test. Scientists and engineers from the U.S., Britain, and Canada proved the feasibility of weaponizing energy from plutonium nuclear fission using an implosion mechanism.

2. Demonstrated the Principles of Thermonuclear Fusion and Boosting

Los Alamos was the first to produce thermonuclear fusion in Operation Greenhouse's George test (1951). Its following test, Item, demonstrated the boosting of fission yield. The concept of hollow-boosting was proved-out in Operation Teapot (1955).

3. Invented the H-bomb

Los Alamos demonstrated the feasibility of radiation coupling between a primary stage and secondary stage, and the feasibility of producing a full-scale thermonuclear explosion, in Ivy-Mike (1952). Los Alamos then successfully designed and tested practical thermonuclear devices in the Operation Castle series (1954), leading the way to U.S. stockpile high-yield weapons. These secondary designs, together with hollow-boosted primary designs, set the template for the U.S. stockpile.

4. Developed Battlefield Nuclear Weapons

By the early- to mid-1950s, Los Alamos had enabled the world's first battlefield nuclear weapons with nuclear warheads for the Army's Honest John and Corporal short-range missiles, the Air Force's Matador cruise missile, and the Army's 11-inch artillery-fired atomic projectile.

5. Pioneered One-Point Safety and Hydronuclear Tests

Los Alamos was a pioneer of one-point safety—the concept of preventing nuclear yield in the event of an unintentional high-explosive detonation. During the 1958-1961 nuclear test moratorium, President Eisenhower authorized innovative hydronuclear tests to elucidate stockpile-related safety issues. These experiments produced modest amounts of fission but were engineered to avoid nuclear explosions.

6. Advanced Strategic Warheads for ICBMs and SLBMs

Los Alamos designed powerful, miniaturized, hardened, W76, W78, and W88 MIRV'd (multiple independently-targetable reentry vehicle) warheads in the 1970s and 1980s. These remain the cornerstone of the U.S. deterrent.

7. Invented Plastic-Bonded Conventional and Insensitive High Explosives (PBX)

Los Alamos invented the plastic bonded conventional high-explosive PBX 9501 to improve safety in handling and transportation scenarios, while maintaining performance and facilitating compact warhead designs. The Lab was also the first to formulate tri-amino-trinitro-benzene (TATB) into insensitive high explosives (IHE), and to test and field nuclear warheads with IHE – the B61, then the W80 and W85 – using PBX 9502.

8. Los Alamos Designed the Majority of the U.S. Stockpile

Historically, of the 63 types of nuclear weapons entered into the U.S. stockpile, three-quarters were Los Alamos designed (46 of 63). Of today's seven types of nuclear weapons, five are Los Alamos designed: the B61 gravity bomb; the W80 cruise-missile warhead; and the W76, W78, and W88 reentry warheads.

9. Los Alamos: DOE's Center of Excellence for Plutonium R&D

Since 1943, Los Alamos has designed a wide variety of pit-types and plutonium alloys tailored to meet specific weapon requirements. The laboratory has the nation's only facility capable of handling large quantities of plutonium for pit manufacturing, power sources, and R&D. It invented the electro-refining process, resulting in routine preparation of ultra high-purity plutonium. Early in its history, Los Alamos first measured the critical mass of plutonium, and to this day leads experimental and simulation work in nuclear criticality and criticality safety.

10. Gas Transfer Systems for Improved Performance Margins

Los Alamos developed gas transfer system technologies to improve overall weapon performance margins and increase component lifetimes. These solid-storage gas transfer systems deliver a boost gas mixture containing negligible helium-3 with nearly constant tritium and deuterium quantities over the lifetime of the system.

LA-UR-19-26645

Top 10 Weapons Breakthroughs in Los Alamos History: Manhattan Project On

Mark B. Chadwick
Chief Scientist/COO for Weapons Physics ALDX, LANL

July 17, 2019

Student Symposium: Scientific and Historic Impacts from the Manhattan Project

Thanks to Alan Carr & Clay Dillingham, Sarah Tasseff & Michael Bernardin for historical references & images

75 Anniversary of the lab last year (1943-2018)

Wall display in NSSB, 6th floor, part of the 75 year celebration

LANL national security missions underpinning nuclear deterrence

Sustaining the current stockpile

- Surveillance and science studies to assess weapons' health; rebuild as needed

Providing options for future stockpile

- What are weapon options that can be developed and certified without further nuclear testing?

Shaping a globalized nuclear world

- What are other countries pursuing regarding nuclear weapons?
- How to avoid technological surprise by our adversaries?
- What response options should the US have available?

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Shaping a globalized nuclear world

- What are other countries pursuing regarding nuclear weapons?
- How to avoid technological surprise by our adversaries?
- What response options should the US have available?

Solemn responsibility: *These are dreadful weapons. Our goal is to provide technical solutions to support the government's deterrence policy*

LANL is the design laboratory for the sea-leg SLBMs, the MIRV-capable ICBMs, and the NATO tactical deterrent

Design: *Physics & Engineering/ Surveillance*
Production: *Plutonium pits; detonators; power sources*

Lifetime Extension Programs: stewarding the US deterrent, to maintain effectiveness

Navy:
W76-0 → W76-1
W76-2 (per Nuclear Posture Review)
W88 → W88-Alt

Air Force:
W78
B61 → B61-12
Variants

Preparing for the future: *"America confronts an international security situation that is more complex and demanding than any since the end of the Cold War", Nuclear Posture Review 2018*

1. Invention of the Atomic Bomb

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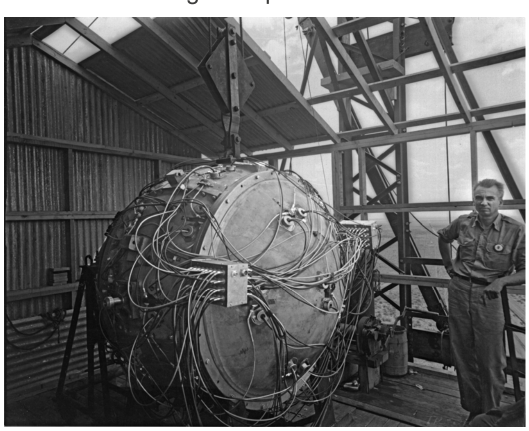

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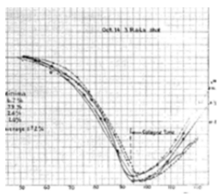
Implosion Mechanism

In 1944 Oppenheimer reorganized the lab to focus on the implosion mechanism for plutonium. This drove design work in HE lens systems and detonators. New diagnostics such as RaLa (radioactive lanthanum) proved essential for optimizing the implosion.



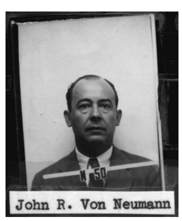
(Also implemented pulsed X-ray radiography & contact wire diagnostics)

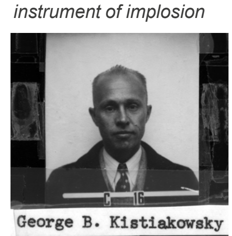
David Hawkins wrote: “RaLa became the most important single experiment affecting the final bomb design”

The scientists leading the implosion concept

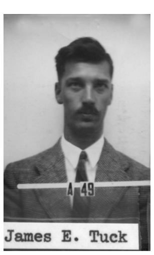
Converging shocks, HE lenses

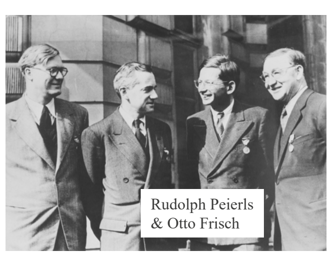
HE as a precision instrument of implosion

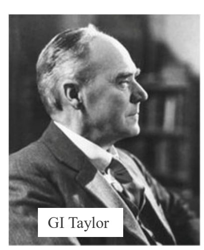


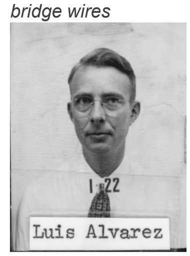


Detonators – exploding bridge wires

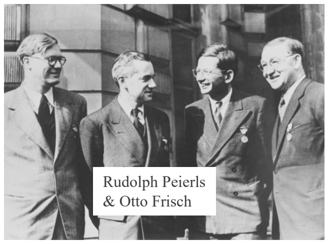








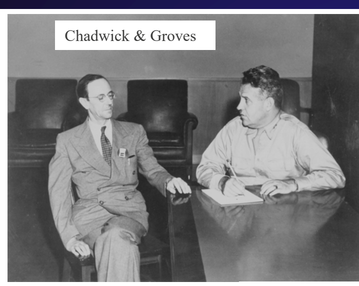
And…


Rudolph Peierls
& Otto Frisch

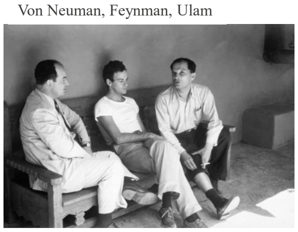
"*You could tell who where the Brits: they were the ones speaking with German accents"* …US Manhattan scientists

I used to have coffee with Peierls as a grad student in Oxford's Nuclear Physics Department. He was also an emeritus Fellow at New College.

1. Others…


Chadwick & Groves


Lawrence, Fermi, Rabi

Von Neuman, Feynman, Ulam


Cyril Stanley Smith, per. Hecker. Head of Metallurgy.
British, naturalized 1940; MIT, & American Brass Company; Alloyed Pu with Ga, making δ


2. Demonstrated the Principles of Thermonuclear Fusion and Boosting

Los Alamos was the first to produce thermonuclear fusion in Operation Greenhouse's George test (1951). Its following test, Item, demonstrated the boosting of fission yield. The concept of hollow-boosting was proved-out in Operation Teapot (1955).

Greenhouse George

Greenhouse Item

Fusion energy

Powers the sun (Eddington's insight, after Einstein's $E=mc^2$)

On earth….

1932 – a big year. The neutron was discovered (James Chadwick)
- first lab accelerator creation of fusion in Cambridge (p+Li -> alphas)

1951 - first fusion in a burning plasma – Los Alamos (Greenhouse George)

Also..

Thermonuclear bombs use fission and fusion

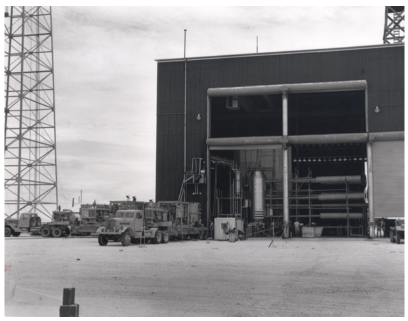
Neutron bomb

National Ignition Facility at Livermore & quest for *ignition*

3. Invented the H-bomb

Los Alamos demonstrated the feasibility of radiation coupling between a primary stage and secondary stage, and the feasibility of producing a full-scale thermonuclear explosion, in Ivy-Mike (1952). Los Alamos then successfully designed and tested practical thermonuclear devices in the Operation Castle series (1954), leading the way to U.S. stockpile high-yield weapons.

Ivy-Mike

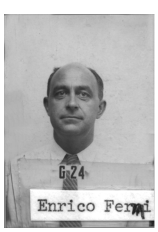


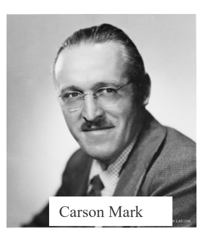
3. Invention of the H-bomb: Ivy Mike & Operation Castle – the people

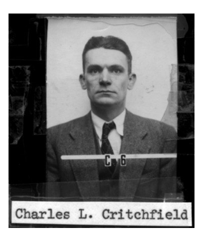
Staging

Radiation implosion

Herb York: *"Teller slighted Ulam. But Teller does deserve 51% of the credit!"*







Dick Garwin, Everett

3. Invention of the H-bomb

These secondary designs, together with hollow-boosted primary designs, set the template for the U.S. stockpile.

John Richter's perspective: *"Castle results can be described as sensational"*

Castle-Yankee

Castle-Union

4. Developed Battlefield Nuclear Weapons

By the early- to mid-1950s, Los Alamos had enabled the world's first battlefield nuclear weapons with nuclear warheads for the Army's Honest John and Corporal short-range missiles, the Air Force's Matador cruise missile, and the Army's 11-inch artillery-fired atomic projectile.

Cannon nicknamed "Atomic Annie"

5. Pioneered One-Point Safety and Hydronuclear Tests

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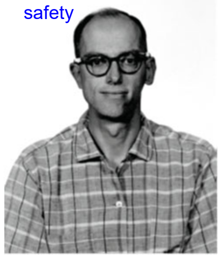
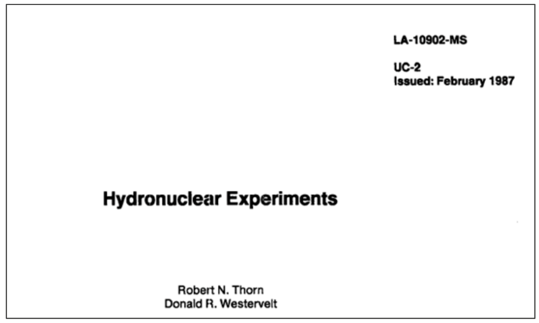
Bob Osborne, Father of one-point safety





LA-10902-MS

UC-2
Issued: February 1987

Hydronuclear Experiments

Robert N. Thorn
Donald R. Westervelt

5.… Design Changes Informed by ~1960 Hydronuclear Tests Prevented Nuclear Yield in Palomares Accident (1966)

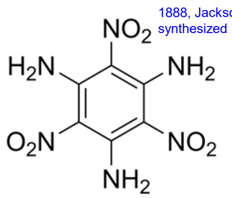
6. Advanced Strategic Warheads for ICBMs and SLBMs

Los Alamos designed powerful, miniaturized, hardened, W76, W78, and W88 MIRV'd (multiple independently-targetable reentry vehicle) warheads in the 1970s and 1980s. These remain the cornerstone of the U.S. deterrent.

7. Invented Plastic-Bonded Conventional and Insensitive High Explosives (PBX)

Los Alamos invented the plastic bonded conventional high-explosive PBX 9501 to improve safety in handling and transportation scenarios, while maintaining performance and facilitating compact warhead designs. The Lab was also the first to formulate tri-amino-trinitro-benzene (TATB) into insensitive high explosives (IHE), and to test and field nuclear warheads with IHE – the B61, then the W80 and W85 – using PBX 9502.

TATB (1,3,5-triamino-2,4,6-trinitro-benzene)



1888, Jackson & Wing first synthesized TATB, at Harvard

Aylor & Kaplan, US Navy, 1959

1961-1966 LANL: Schwartz, … Benziger (patent, pilot plant)

TATB $C_6H_6O_6N_6$ | HMX $C_4H_8O_8N_8$ | PETN $C_5H_8O_{12}N_4$

Cary Skidmore, LANL: "(U) PBX 9502 – Uniquely Suited for Nuclear Bombs"

8. Los Alamos Designed the Majority of the U.S. Stockpile

Historically, of the 63 types of nuclear weapons entered into the U.S. stockpile, three-quarters were Los Alamos designed (46 of 63). Of today's seven types of nuclear weapons, five are Los Alamos designed: the B61 gravity bomb; the W80 cruise-missile warhead; and the W76, W78, and W88 reentry warheads.

Source:
M. Bernardin, Strategic Arms Competition During the Cold War 1945 to 1959

(Counts B61 family just once!)

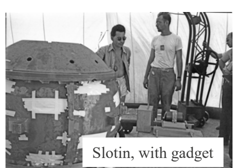
LANL				LLNL			
No	Warhead	Delivery Systems[1]	Dates in Stockpile[2]	No	Warhead	Delivery Systems	Dates in Stockpile
1	Fat Man	Bomb	1945-49				
2	Little Boy	Bomb	1945-50				
3	B3	Bomb	1945-51				
	T4	ADM	1958-63				
4	B4	Bomb	1949-53				
5	B5 W5	 Matador/Regulus	1952-63 1952-63				
6	B6	Bomb	1951-62				
7	B7 W7	 Corporal, Honest John, BOAR, Betty, Nike-Hercules	1952-67 1953-67				
8	B8	Penetrator bomb	1951-56				
9	W9	280mm AFAP	1952-57				
10	B11	Penetrator bomb	1956-60				
11	B12	Bomb	1954-63				
12	B14	Bomb	1954				
13	B15	Bomb	1955-65				
14	B17	Bomb	1954-57				
15	B18	Bomb	1953-56				
16	W19	280mm AFAP	1956-63				
17	B21	Bomb	1955-57				
18	W23	16in AFAP	1956-59				
19	B24	Bomb	1954-57				
20	W25	Genie, Little John	1957-84				
				1	B27 W27	 Regulus	1958-65 1958-65
21	B28 W28	 Hounddog, Mace	1958-91 1958-76				
22	W30	Talos	1959-78				
23	W31	Nike-Hercules, Honest John, ADM	1958-89				
24	W33	8in AFAP	1956-92				
25	W34	Astor, Hotpoint, Lulu	1958-77				
26	B36	Bomb	1956-62				
				2	W38	Atlas, Titan	1961-65
27	B39 W39	 Redstone, Snark	1957-66 1958-65				

[1] Nuclear Matters Handbook
[2] That a specified weapon is in a specified DOE weapon program phase is U (CG-LANL-COMP-1, Aug. 2009); Ref: Annual Weapons Program Report, FY1996 and FY2010.

LANL				LLNL			
No	Warhead	Delivery	Dates	No	Warhead	Delivery	Dates
28	W40	Bomarc, Lacrosse	1959-72				
				3	B41	Bomb	1960-76
29	B43	Bomb	1961-91				
30	W44	ASROC	1961-89				
				4	W45	Bulpup, Little John, Terrier	1962-88
				5	W47	Polaris A1 Polaris A2	1960-75 1963-75
				6	W48	155mm AFAP	1963-92
31	W49	Atlas, Titan, Thor, Jupiter	1958-75				
32	W50	Pershing I	1963-91				
33	W52	Sergeant	1962-77				
34	B53 W53	 Titan II	1962-97 1962-87				
35	B54	SADM	1964-89				
				7	W55	SUBROC	1964-90
				8	W56	Minuteman II	1964-93
36	B57	Depth charge	1963-92				
				9	W58	Polaris A3	1964-82
37	W59	Minuteman I	1962-70				
38	B61	Bomb	1969-				
				10	W62	Minuteman III	1970-2009
39	W66	Sprint SAM	1974-86				
				11	W68	Poseidon	1970-93
40	W69	SRAM	1972-94				
				12	W70	Lance	1973-92
				13	W71	Spartan	1975-92
41	W72	Walleye	1970-79				
42	W76	Trident I	1978-				
43	W78	Minuteman III	1979-				
				14	W79	8in AFAP	1981-92
44	W80	ALCM TLAM	1982- 1984-2010				
				15	B83	Bomb	1983-
				16	W84[3]	GLCM	1983-1990
45	W85	Pershing II	1983-91				
				17	W87	MX	1986-
46	W88	Trident II	1988-				

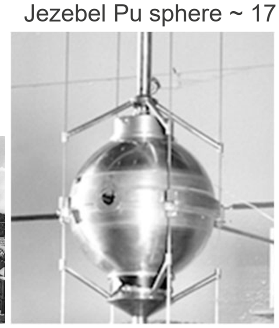
9. Los Alamos: DOE's Center of Excellence for Plutonium R&D

Since 1943, Los Alamos has designed a wide variety of pit-types and plutonium alloys tailored to meet specific weapon requirements. The laboratory has the nation's only facility capable of handling large quantities of plutonium for pit manufacturing, power sources, and R&D. It invented the electro-refining process, resulting in routine preparation of ultra high-purity plutonium. Early in its history, Los Alamos first measured the critical mass of plutonium, and to this day leads experimental and simulation work in nuclear criticality and criticality safety.


Slotin, with gadget

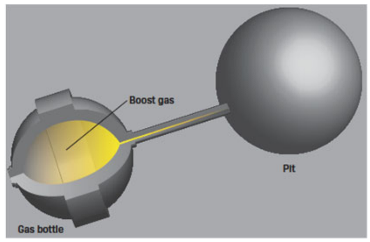

Daghlian, carrying plutonium

Jezebel Pu sphere ~ 17 kg



10. Gas Transfer Systems for Improved Performance Margins

Los Alamos developed gas transfer system technologies to improve overall weapon performance margins and increase component lifetimes. These solid-storage gas transfer systems deliver a boost gas mixture containing negligible helium-3 with nearly constant tritium and deuterium quantities over the lifetime of the system.



W76-1/Mk4A
NNSA LANL SNL
DoD SSP LMSS
TRIDENT II

W88/Mk5
ALT 370
NNSA SNL LANL KCNSC PX Y12 DOD SSP LMSSC

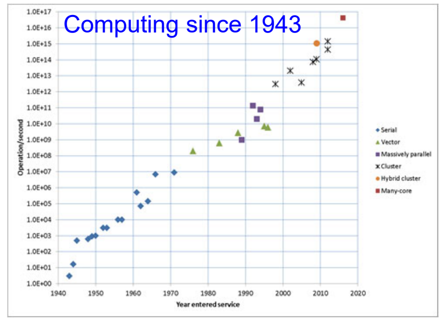
B61-12
LIFE EXTENSION
NNSA - KCP - LANL - PX - SNL - SRS - Y-12 - USAF

What might a "Top 10 scientific tools for stockpile stewardship look like"? Some personal thoughts…

1. **Accelerators & dynamic radiography – flash X-rays (1943-today) ; proton radiography (1990s- today)**
2. **Computing – Monte Carlo method (1940s); first to peta-flop (2018), towards exascale (2020s)**
3. **MCNP neutron radiation transport code, & other codes**
4. **Hydrodynamics and turbulence (RT, RM,….) theory and computation**
5. **Materials – nuclear cross sections (ENDF), opacity, equation of state (EOS) databases & material models; novel materials production & qualification**
6. **Nuclear criticality, 1940s – today in Nevada (LANL-run NCERC)**
7. **Nuclear radiochemistry – diagnostics & forensics (*e.g.* detection of Joe's)**
8. **Space satellites for nuclear detection (NuDet), Vela (1960s)-today**
9. **Exquisite diagnostics to understand nuclear tests – PINEX, NUEX, ….**
10. **Subcritical experiments in Nevada /U1a facility (1990s-present)**
11. **…. Add your favorite!**

Lessons learned

- **Scientific and engineering excellence is at the heart of deterrence**
  - a broad portfolio of basic and applied science helps us recruit the best, including researchers from overseas! ***Manhattan project set the standard***
- **We must grow a skilled workforce to address tomorrow's needs & threats**
  - "stockpile responsiveness"
  - continued innovation is essential
  - advance our "design" skills
- **Computing/simulation advances have been remarkable**
  - yet we must tie & validate our understanding to real-world experiments



- **Although stewardship has been a success, with remarkable facilities (ASC, DARHT, LANSCE, NIF, Z, …), material manufacturing has had problems**
  - we must reestablish efficient production (pits, U components, HE, …)
  - and we should never stop production!

Our greatest scientific challenges ahead

Since we can't test anymore, we are guided by high performance computer simulations and laboratory experiments, but gaps exist:

- **high-compression Pu /radiography** *(LANL & Nevada, with LLNL, SNL)*
- **materials: μ–structure to performance** *(LANL, DOE/Science experience)*
- **burning thermonuclear plasmas** *(collaborations with LLNL, SNL)*
- **3D codes/algorithms on future HPC architectures** *(all labs)*

Gaps inform NNSA future facility investment strategy

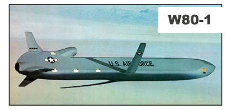
Delivering on our weapons mission depends on a skilled workforce that is excited by these science & technology challenges

The US stockpile that we are sustaining

Bombs

B61-3 B61-4 B61-7 B61-11
(1979) (1979) (1985) (1996)
(FPU date)

(1983)



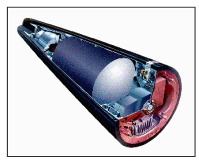
(1982)

ICBMs

(1979)

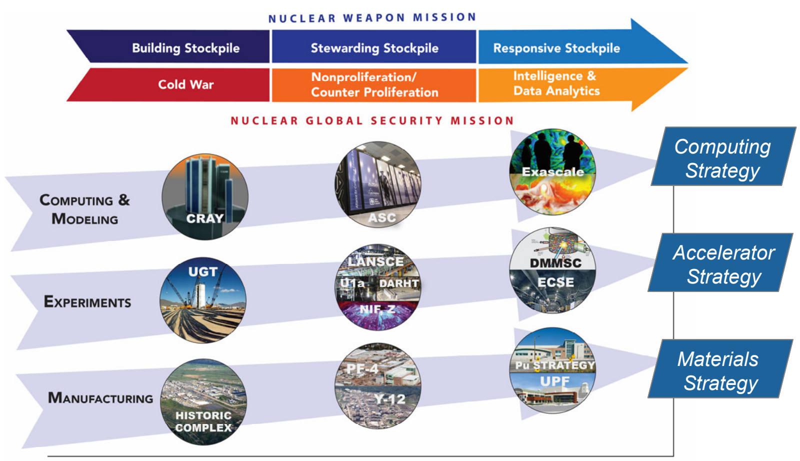
(1986)

SLBMs



(1978) (2008)

An enduring future for an integrated Laboratory
— and the need for integrating assets at scale for national security

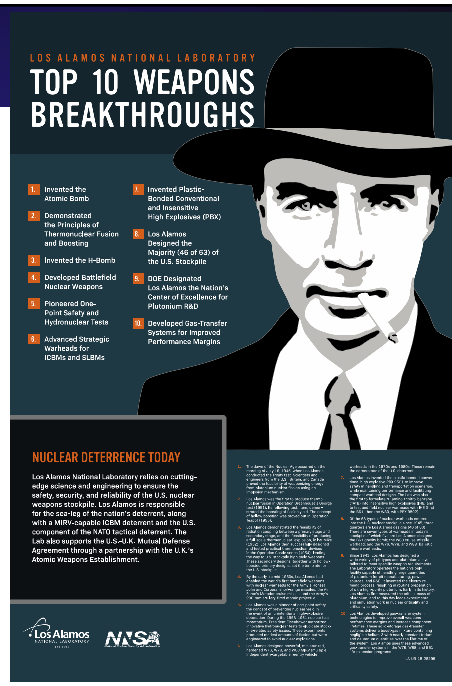


A Guiding Philosophy from our First Director

"There must be no barriers for freedom of inquiry. There is no place for dogma in science. The scientist is free, and must be free, to ask any question, to doubt any assertion, to seek for any evidence, to correct any errors."

J. Robert Oppenheimer

Top 10 posters around the lab



7… cont. Some dates for IHE entering the US stockpile

1979. LANL B61

1982. LANL W80-1 ALCM (Dec.)

1983. LANL W85: Phase 5 FPU in May; Phase 6 Steady Production May; IOC Dec

1983. LLNL B83, W84: Phase 5 FPU in May, Phase 6 September: IOC Dec

LANL had fielded 3 IHE systems before
LLNL started to field IHE

Plutonium: Manhattan Project to Today

Siegfried S. Hecker
Center for International Security and Cooperation Stanford University

LA-UR-19-27496

Plutonium symbolizes everything we associate with the nuclear age. It evokes the entire gamut of emotions from good to evil, from hope to despair, and from the salvation of humanity to its utter destruction. No other element bears such a burden. Its discovery in 1941, following the discovery of fission in 1938, unlocked the potential and fear of the nuclear age.

On March 28, 1941, Kennedy, Seaborg, Segre, and Wahl first demonstrated that Pu-239 undergoes slow neutron-induced fission with a cross section that was approximately 50% greater than that for U-235, releasing millions of times the energy typically released in chemical explosives. This discovery opened the second path to an atomic bomb. The physics of plutonium bombs turned out to be challenging because the gun-assembly technique developed for uranium bombs was too slow, requiring a much more complicated spherical implosion technique. Just as challenging were developing the chemical, metallurgical and engineering methods to craft plutonium into such spherical assemblies.

Manhattan Project scientists and engineers managed the incredible feat of taking the discovery by Glenn Seaborg and colleagues in less than three years to expand plutonium production from micrograms to the kilograms required for the nuclear bomb that destroyed Nagasaki. What made this feat even more remarkable was that plutonium turned out to be the most complex element in the periodic table.

As element 94, it fits near the middle of the actinide series. It is the 5*f* electrons that make plutonium extraordinarily complex. With little provocation, the metal changes its density by as much as 25%. It can be as brittle as glass or as malleable as aluminum; it expands when it solidifies— much like water freezing to ice; and its shiny, silvery, freshly machined surface will tarnish in minutes. It is highly reactive in air and strongly reducing in solution, forming multiple compounds and complexes in the environment and during chemical processing. It transmutes by radioactive decay, causing damage to its crystalline lattice and leaving behind helium, americium, uranium, neptunium, and other impurities. Plutonium damages materials on contact and is therefore difficult to handle, store, or transport. Who would ever dream of making and using such a material? Physicists did during the Manhattan Project—to take advantage of the nuclear properties of Pu-239.

These peculiarities of the newly-created metal were discovered one surprise after another during the frantic years of 1943 to 1945 as the reactors at Oak Ridge and Hanford produced sufficient quantities of plutonium metal to permit characterization. For example, as late as 1944 the measured density of plutonium metal varied from 11 g/cc to 22 g/cc because surface reactivity led to severe oxidation and plutonium metal was found to exhibit multiple crystallographic forms, with the room-temperature phase appearing to be brittle as glass. A reproducible density is critical to bomb design and having plutonium metal exhibit some ductility was highly desirable for manufacturability.

In a remarkable effort in 1944, Cyril Stanley Smith, the lead metallurgist at Los Alamos, and his colleagues conducted an alloy survey program that led to the production of a face-centered cubic form of plutonium with a reproducible density of roughly 15.75 g/cc that exhibited ductility akin to that of commercially pure aluminum, rather than glass. The magic formulation consisted of adding approximately 3.5 atomic percent gallium to plutonium before casting, which led to the retention of the fcc δ-phase to room temperature. It was recognized that this phase likely is in a metastable state, but anticipated requirements were viewed to be months, not years or decades. The "long-time stability" study of the material ran out of time at 44 days because the first devices needed to be fabricated.

The surface of plutonium metal also proved problematic in that plutonium oxidized at dramatic rates in certain environments, requiring coating the plutonium components. The remarkable progress in taming this complex element made by chemists, metallurgists, and engineers during the Manhattan Project is described by one of the pioneers, Edward Hammel, in *"Plutonium Metallurgy at Los Alamos, 1943 to 1945.*"[1]

During the Cold War, the primary interest in plutonium was to provide triggers for thermonuclear weapons for a triad of delivery means (namely, weapons delivered by bombers, land-based missiles and sea-launched missiles) that formed the basis of nuclear deterrence. Both the engineering requirements encompassing a large range of temperatures and stresses and the physics requirements for successful detonation became increasingly more demanding as the nuclear devices were designed to be smaller and lighter. The manufacturing requirements likewise increased as the United States scaled up not only the sophistication of its weapons, but also dramatically increased their number.

The manufacturing role shifted to the Rocky Flats Plant in 1952. The Los Alamos laboratory continued to play the lead role in the U.S. nuclear complex in plutonium alloy development and property characterization during the Cold War, although significant efforts were mounted at the Lawrence Livermore laboratory along with early efforts at Argonne and Pacific Northwest laboratories. Moreover, President Eisenhower's Atoms for Peace initiative launched in December 1953 led to international collaboration on the fundamental properties of plutonium. The first international conferences describing some of this work were the International Conferences on the Peaceful Uses of Atomic Energy held in Geneva in 1955 and 1958. International conferences dedicated primarily to plutonium were held in 1965, 1970 and 1975, followed later by a variety of such conferences on plutonium and the actinides. The first edition of the plutonium handbook, *Plutonium Handbook: A Guide to the Technology*,[2] was published in 1967. David Clark is leading the effort at Los Alamos to publish a seven-volume update.

[1] Plutonium Metallurgy at Los Alamos, 1943-1945: Recollections of Edward F. Hammel by Edward F. Hammel (1998-12-03), Los Alamos Historical Society. Also summarized in *Los Alamos Science,* 2000, No. 26, p. 48.
[2] O.J. Wick, ed. Plutonium Handbook: A Guide to Technology, Gordon & Breach Science Publishers (1967)

As a brief introduction to plutonium science, I present the unusual properties of plutonium in Table 1 to give the reader an appreciation for the complexities of plutonium. The greatest engineering challenges arise from its notorious instability as shown in Figure 1. Plutonium metal is unstable with respect to temperature, pressure, chemical additions, and time. The metallurgical challenges for engineering applications of plutonium are particularly great because of its instability and the myriad of phase transformations it exhibits.

Plutonium defies conventional metallurgical wisdom, so we must turn to its electronic structure to gain better insight. Many of the properties described above are telltale signs of novel interactions and correlations among electrons. Boring and Smith[3] point out that such novel interactions typically result from a competition between itinerancy (bonding electrons that form bands in metals) and localization (electrons with local moments that magnetically order at low temperature).

The actinides mark the filling of the 5*f* atomic subshell much like the rare earths mark the filling of the 4*f* subshell. Yet, the 5*f* electrons of the light actinides behave more like the 5*d* electrons of the transition metals than the 4*f* electrons of the rare earths. At the very beginning of the actinide series, there is little *f*-electron influence and, hence, one finds typical metallic crystal structures, few allotropes, and high melting points (this behavior is best illustrated in the connected phase diagram across the actinides in Figure 2). As more *f* electrons are added (up to plutonium), they participate in bonding (that is, they are itinerant, much like the *d* electrons in transition metals) and the crystal structures become less symmetric, the number of allotropes increases, and the melting points decrease. At americium and beyond, crystal structures typical of metals return, the number of allotropes decreases, and the melting points rise — all indications of the *f* electrons becoming localized or chemically inert, like the 4*f* electrons in the rare earths.

Figure 2 demonstrates that the peculiar properties of plutonium are not a single anomaly, but rather the culmination of a systematic trend across the actinides. The transition between bonding and localization of the 5*f* electrons occurs not between plutonium and americium, but right at plutonium. In fact, atomic volume measurements show that the transition occurs between the ground-state α-phase and the elevated-temperature δ-phase.

The publication of the *Los Alamos Science* volumes on *Challenges in Plutonium Science*, sparked a resurgence of interest in studying the fundamental properties of plutonium. And about the same time, we experienced a new programmatic challenge in that nuclear testing was banned by the Comprehensive Test Ban Treaty a few years after the end of the Cold War. Consequently, certifying the safety and reliability of the nuclear weapons remaining in the arsenal required a stockpile stewardship program that placed a premium on understanding plutonium better because we were no longer able to conduct the nuclear proof tests that allowed us to bridge the gap between our understanding of physics and actual weapon function.

The end of the Cold War dramatically altered the military postures of the United States and Russia, allowing each to reverse the engines fueling the nuclear-weapons buildup. The nuclear arsenals of the two countries have been decreased by 85%. Both countries faced the challenge of keeping the remaining stockpile of nuclear weapons safe and reliable without nuclear testing, as

[3] A.M. Boring and J.L. Smith, Los Alamos Science, No. 26, 2000, Los Alamos National Laboratory, p. 90.

well as cleaning up nuclear contamination in the nuclear weapons complex and preventing the spread of nuclear weapons and nuclear terrorism.

Unexpectedly, the end of the Cold War also allowed American and Russian nuclear scientists to work together on nuclear safety and security issues, as well as fundamental science problems of common interest. One unresolved problem was the question of metastability of the fcc δ-phase in alloyed plutonium. I was able to work with Russia's premier plutonium metallurgist, Dr. Lidia Timofeeva, to resolve previous differences in Russia's favor as described in the "Tale of Two Diagrams."[4]

The next major challenge in plutonium science and technology was to understand the aging of plutonium because the end of nuclear testing and the closure of U.S. plutonium manufacturing facilities at the Rocky Flats Plant required a life-time extension for the plutonium components in U.S. weapons to many decades. In addition to typical concerns of materials aging from the outside in through surface reactions, plutonium ages from the inside out because of the relentless deposition of energy from its alpha decay, which damages its crystal lattice and transmutes plutonium into other elements over time (principally, helium, americium, uranium, and neptunium).

At cryogenic temperatures (4 K), lattice damage causes an apparent loss of crystallinity at long irradiation times. At room temperature, much but not all of the lattice damage is annealed out because defects produced by self-irradiation are sufficiently mobile. Small nanometer-size bubbles form quite rapidly. Much effort continues to be devoted to understand the effect of these bubbles and other changes with age on the properties and performance of plutonium, particularly since self-irradiation may affect plutonium's delicate balance of stability with changes in temperature, pressure, or chemistry.

My journey with plutonium also diversified from its scientific roots that began with a summer research internship at Los Alamos in 1965 and continued through my responsibilities for stockpile stewardship both as a scientist and laboratory director. With the dissolution of the Soviet Union, my interests also turned to assisting other countries to provide security for their inventories of plutonium, be it in military or civilian programs. These efforts took me many times to Russia, also to its former nuclear test site, now in Kazakhstan. I also had occasion to visit the Indian and Pakistani nuclear sites, and remarkable visits to North Korea's nuclear complex and its plutonium laboratories.

Plutonium, and nuclear materials, offer the prospects of peace and prosperity through judicious military employment and civilian use, such as nuclear electricity, nuclear medicine and nuclear batteries. However, they also hold the potential seeds of war and disaster if not managed properly. We depend on the next generation to be able to manage this balance so that we can look back at the 100th anniversary of the Manhattan Project and be able to declare it a success.

[4] S.S. Hecker and L.F. Timofeeva, "A Tale of Two Diagrams," *Los Alamos Science,* No. 26, 2000, p. 244.

Table 1: Unusual properties of plutonium

- Unique low-symmetry crystal structures
- Six allotropic phases (seventh under pressure)
- fcc phase is least dense and highly elasticallyanisotropic
- Dramatic volume changes
- Extreme sensitivity to alloying
- Low melting point
- Low cohesive energy
- Large specific heats
- Volume decrease upon melting
- Anomalies in low-temperature transport properties
- Dramatic variation in mechanical properties
- Very high self-diffusion in bcc epsilon phase
- Highly unusual properties of the liquid phase
- Great affinity for oxygen and hydrogen
- Very large thermal expansion coefficients
- Negative thermal expansion in fcc phase
- Self-irradiation damage because of radioactive decay.

Figure 1: Instability of plutonium metal

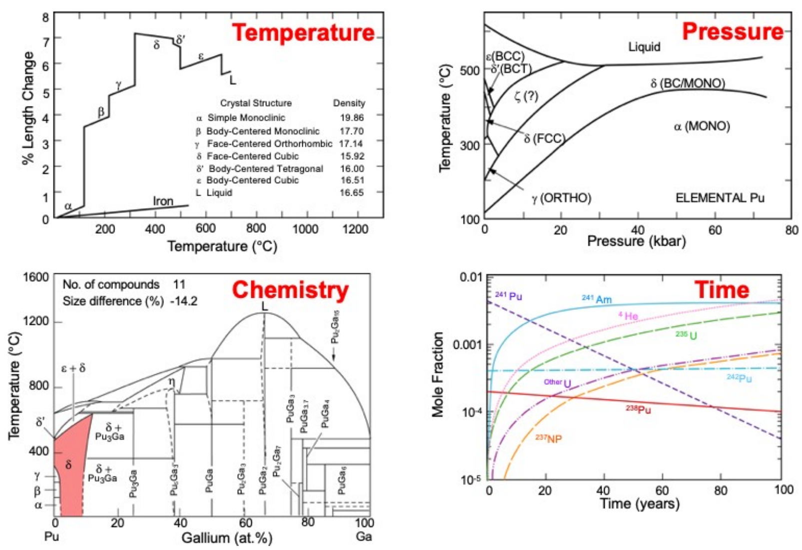
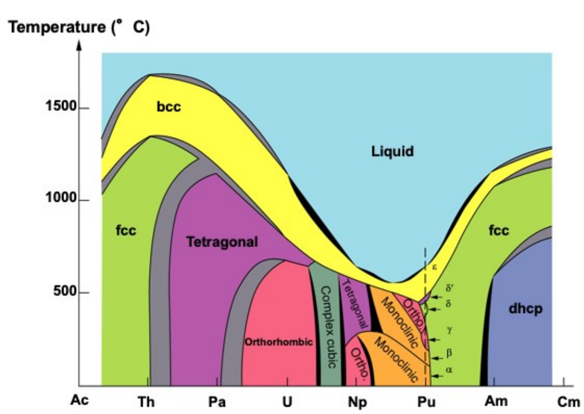
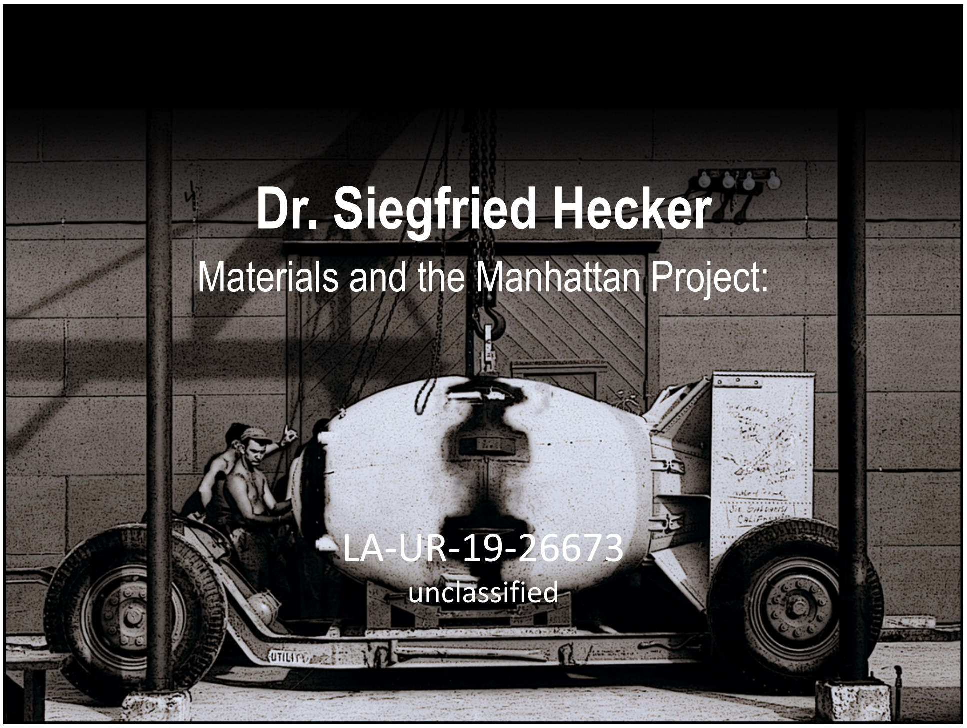


Figure 2. Connected actinide phase diagram (Smith and Kmetko, J.Less Common Metals, 90, p. 83, 1983)





Plutonium: Manhattan Project to Today

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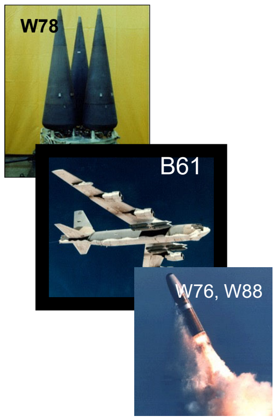
Stanford University

Scientific and Historic Impacts from the Manhattan Project Student Symposium

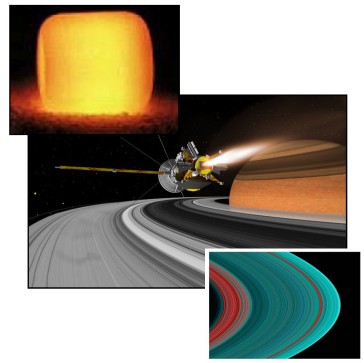
Los Alamos National Laboratory
July 17, 2019

Plutonium – why we care



Nuclear weapons

Nuclear electricity

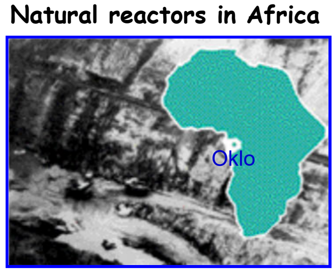


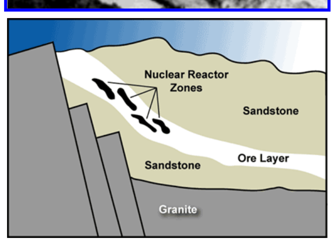
Nuclear batteries

Plutonium - the "man-made" element was first produced in nature

Supernovae

Natural reactors in Africa



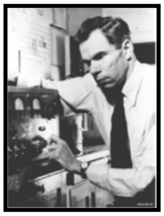


~ 1.7 billion years ago

Seaborg
McMillan
Kennedy
Wahl
1940-1941

Discovery of plutonium – element 94

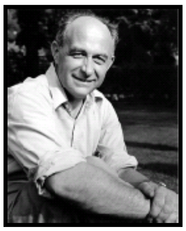
Seaborg
McMillan
Kennedy
Wahl
1940-1941



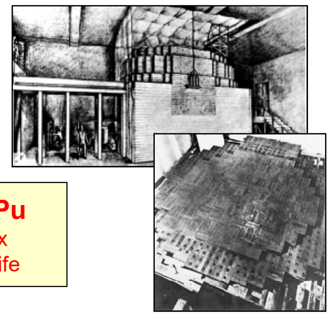
UC Berkeley Cyclotron

^{238}U + ^{2}H $\Rightarrow$ ^{238}Np + 2n
^{238}Np $\Rightarrow$ β^{-} $\Rightarrow$ ^{238}Pu (87.7 year half life)

Fermi,
Szilard,
et al.
Dec. 2,
1942



University of Chicago
Stagg Field

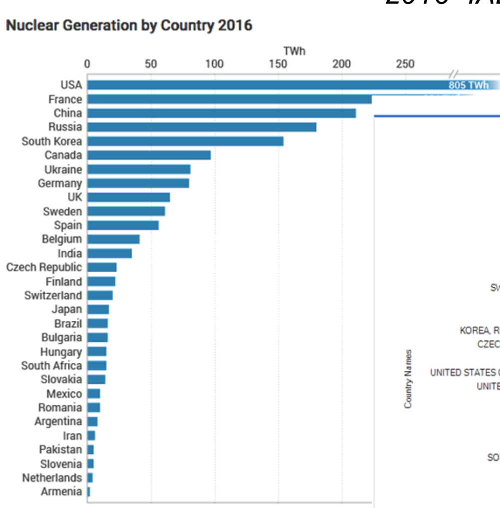


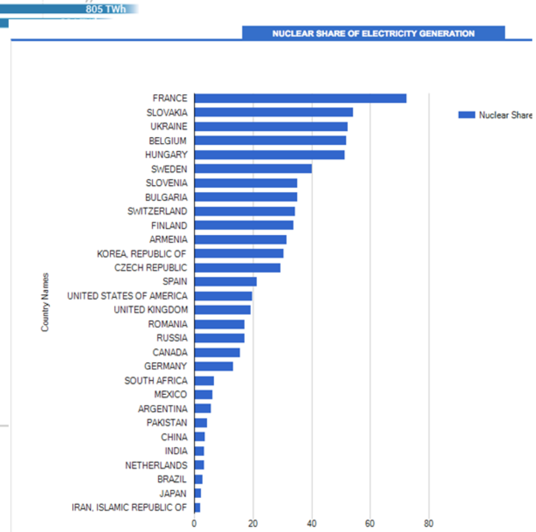
^{238}U + n $\rightarrow$ ^{239}Pu
High neutron flux
24,100 year half life

It was immediately recognized that the "factor of millions" could be used for military or peaceful purposes

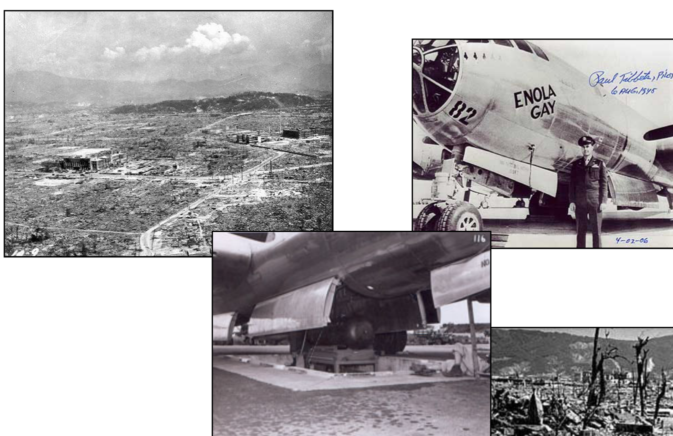
Nuclear energy can electrify the world

2016- IAEA





Hiroshima – one bomb, not a campaign



Hiroshima, August 1945
1 B-29
4.7 sq. miles destroyed
140,000 – 150,000 dead

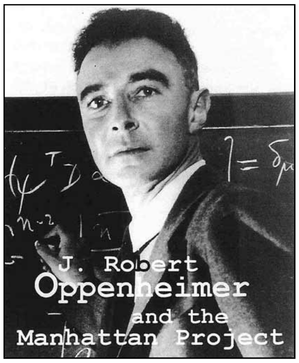
“The sky was dark as pitch, covered with dense clouds of smoke; under that blackness, over the earth, hung a yellow-brown fog. Gradually, the veiled ground became visible and the view beyond rooted me to the spot with horror. All the buildings I could see were on fire… Trees on the nearby hills were smoking, as were the leaves of sweet potatoes in the fields. To say that everything burned is not enough. The sky was dark, the ground was scarlet, and in between hung clouds of yellowish smoke. Three kinds of color – black, yellow, and scarlet – loomed ominously over the people, who ran about like so many ants seeking to escape… That ocean of fire, that sky of smoke! It seemed the end of the world.”

T. Akizuki, eyewitness. *Nagasaki 1945* (Quartet, 1981) Quoted in C. Sagan and R. Turco, *A Path Where No Man Thought: Nuclear Winter and the End of the Arms Race,* Random House, 1990.

August 1945 changed the world forever

“A factor of millions”
by splitting the nucleus

Mankind realized its own mortality with the devastation at Hiroshima and Nagasaki *(Richard Rhodes: Making of the Atomic Bomb)*

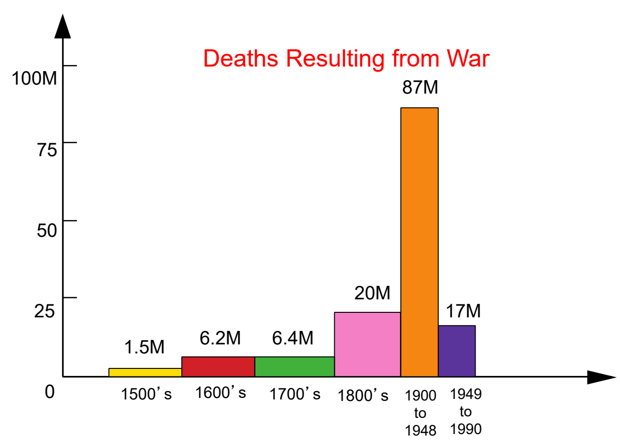


"The atomic bomb made the prospect of future war unendurable. It has led us up those last few steps to the mountain pass;

and beyond there is a different country"

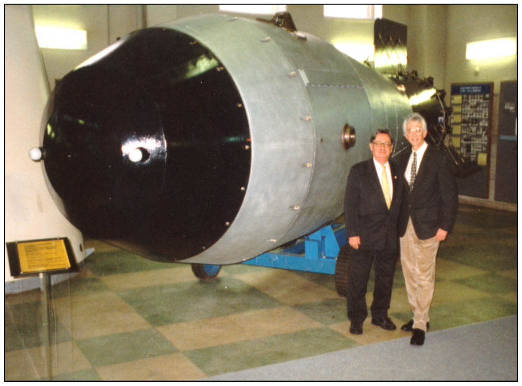
J. Robert Oppenheimer
Director, Los Alamos Laboratory
Scientific Leader, Manhattan Project

Atomic bombs caused a discontinuity in world affairs



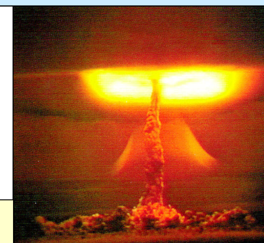
Rough estimates of deaths in war

During Cold War U.S. and Soviet Union "deterred" each other with threat of assured destruction



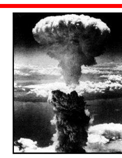
Designer Yuri Trutnev. "Tsar Bomba" 100+Megatons

Test at half-yield over Novaya Zemlya
Oct. 30, 1961



With tens of thousands of bombs, it was at best an uneasy peace – and we were lucky.

Why we have to get plutonium right

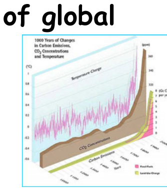


- Nuclear weapons
  - Potential end of life as we know it

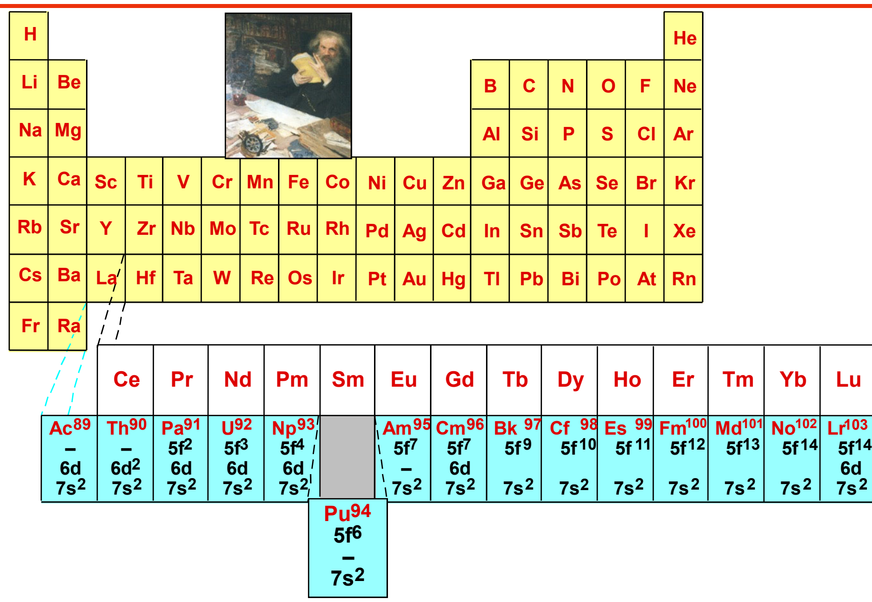
- Nuclear proliferation and terrorism
  - Threat to democracies and way of life

Cover Credit: MATT MAHURIN

- Nuclear energy
  - To help avoid catastrophic consequences of global climate change and potential disruptions
  - Nuclear batteries – space exploration



“Factor of millions” in energy is derived from neutrons.
Plutonium’s complexity arises from its electronic structure



The early plutonium challenges

- Making plutonium metal
- Scaling up production
- Resolving the density problem
- Dealing with the impurity problem
- Dealing with multiple phases
- Retaining and stabilizing the delta phase
- Fabrication of the hemispheres for Trinity and Nagasaki

E.F. Hammel

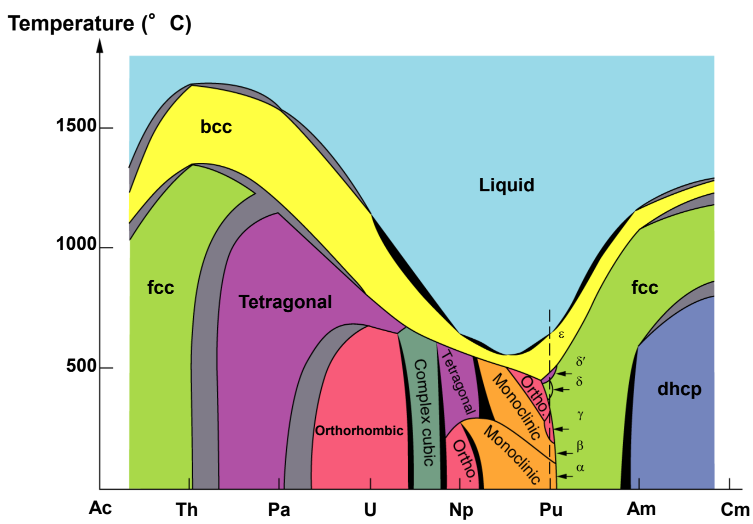
Los Alamos

Unusual properties of plutonium

- Unique low-symmetry crystal structures
- Six allotropic phases (seventh under pressure)
- fcc phase is least dense and highly elastically anisotropic
- Dramatic volume changes
- Extreme sensitivity to alloying
- Low melting point
- Low cohesive energy
- Large specific heats
- Volume decrease upon melting
- Anomalies in low-temperature transport properties
- Dramatic variation in mechanical properties
- Very high self-diffusion in bcc epsilon phase
- Highly unusual properties of the liquid phase
- Great affinity for oxygen and hydrogen
- Very large thermal expansion coefficients
- Negative thermal expansion in fcc phase
- Self-irradiation damage because of radioactive decay

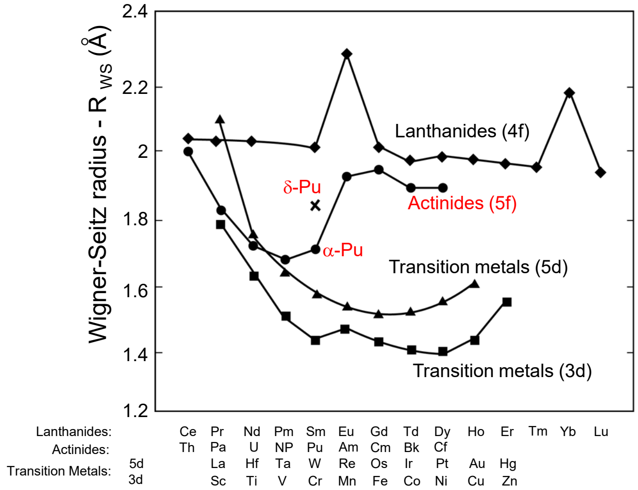
The physicists could not have picked a more challenging engineering material than plutonium for the bomb

The experimental connected actinide phase diagram

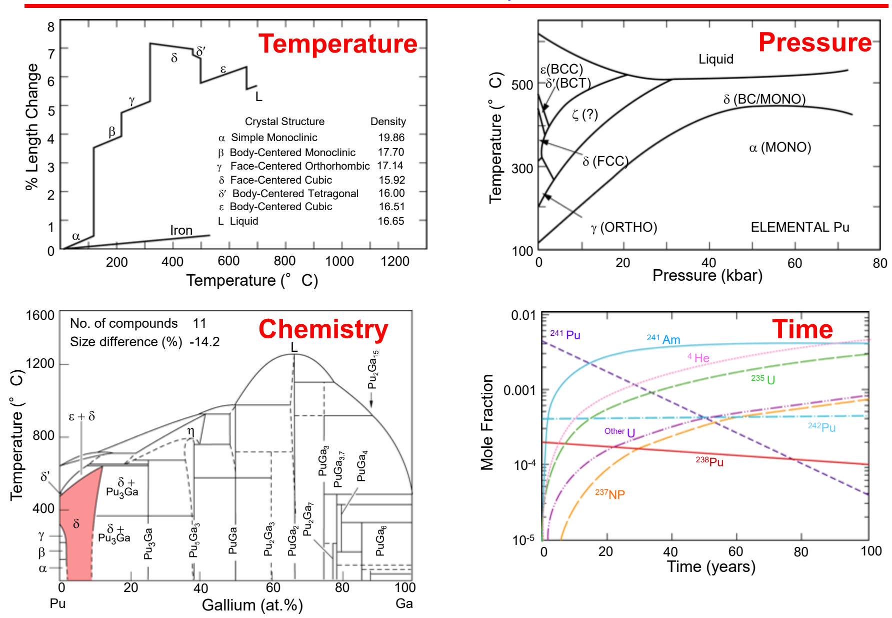


[Smith and Kmetko, 1983]

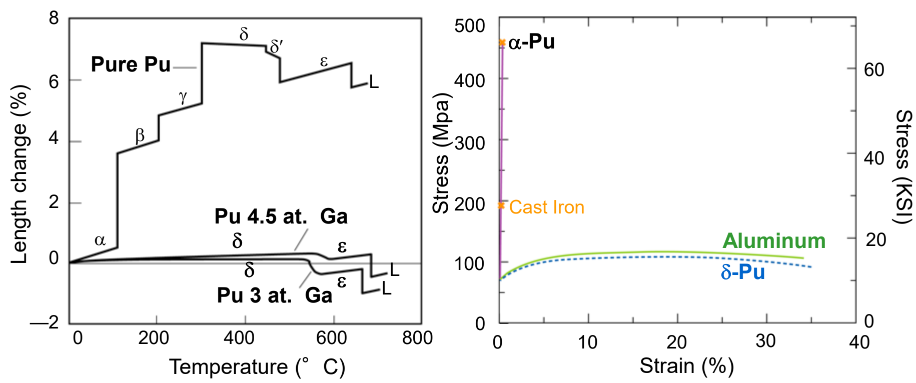
Wigner-Seitz atomic radii for the actinides, the rare earths, and the 3*d* and 5*d* transition metals



Plutonium is notoriously unstable

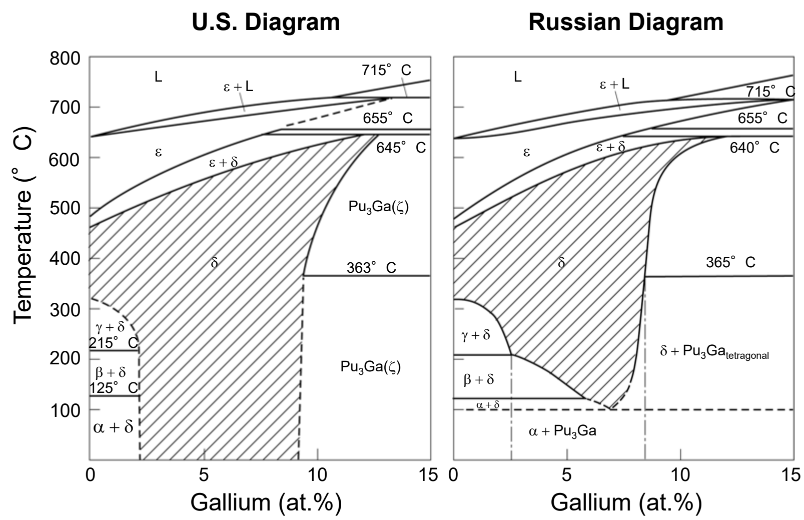


Adding Ga to Pu retains the fcc δ-phase



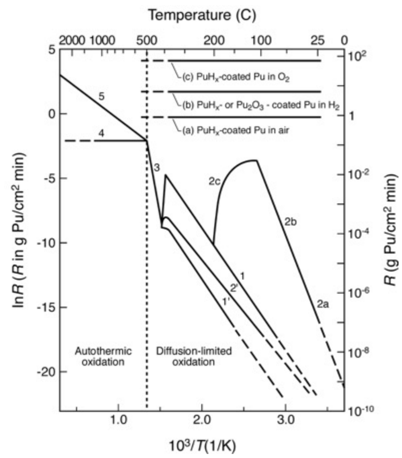
A few atomic percent Ga make plutonium easier to cast and to shape...
but how stable is it?

We are now convinced that Russian version of Pu-Ga phase diagram is the correct "equilibrium" diagram



We would have preferred to be saved by thermodynamics
rather than kinetics

In dry air at room temperature the reactive plutonium surface is passivated by a layer of PuO_2

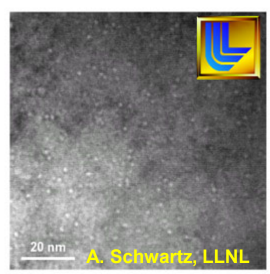


- However, water and hydrogen can catalyze the oxidation reaction to proceed up to 10^{13} faster

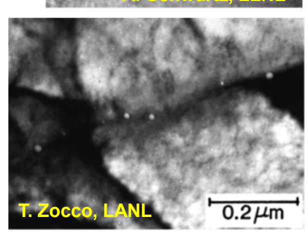
In dry air Pu oxidizes at <0.2μm/yr, whereas in hydrogen at atmospheric pressure it oxidizes at 20 cm/hr.

Potential aging effects in plutonium alloys

- **Surface reactions**
- **Metallurgical changes**
  - Diffusional / thermal activation
  - Phase stability / dimensional changes
  - Residual stresses



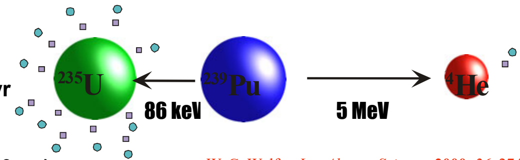
- **Self-irradiation effects**
  - Lattice damage
  - Transmutation products
    - Am, Np and U
    - Helium
  - Void swelling
  - Irradiation embrittlement
  - Irradiation-induced segregation or creep



Self-irradiation damage in plutonium

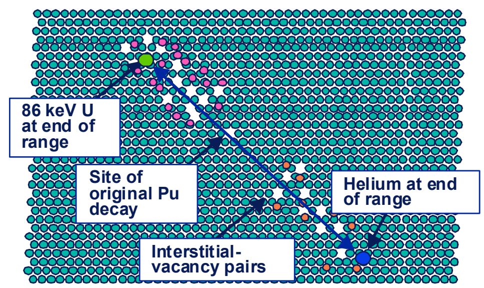
α-decay event

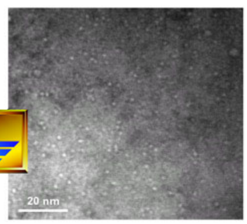
- ^{239}Pu: α-decay: $t_{1/2}$ = 24,000 yr
  - 2.3 x 10^9 α events/gram/s



W. G. Wolfer, *Los Alamos Science*, **2000**, *26*, 274

- Primary defect production (100 ps)
  - Collision cascade with clustering & recombination
  - ~ 20,000 displacements/event
  - ~ 90% immediately recombine
  - ~ 2500 Frenkel pairs/event
  - 0.1 displacements/atom/year (dpa)





Nano-bubbles in aged Pu

Life extension and re-manufacturing are the principal challenges in a no-test era

Typical plutonium requirements

Engineering Structural Performance

- Temperature excursions
- Mechanical loads (g-loads,…)
- Hostile environments
- Life cycle issues (aging, …)

- Dimensions (tolerances, stability,...)
- Structural integrity (cracks, voids,..)
- Compatibility
- Surface reactions/integrity

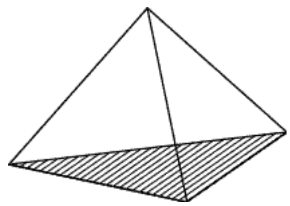
Physics Performance

- Implosion (large deformations)
- Shock loading
- T, P excursions

- Reactivity
- Shape
- Mix

Understanding processing-structure-properties relationship is important for re-manufacturing and life extension

PERFORMANCE



PROCESSING
- Casting
- Heat Treating
- Mechanical Work
- Machining
- Bonding
- Welding
- Cleaning

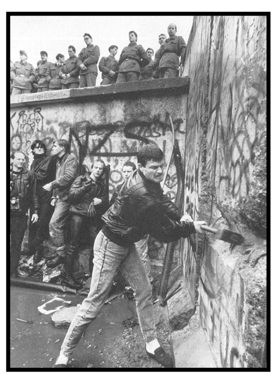
STRUCTURE
- Grain Size
- Ga Segregation
- Second-phase structure
- Impurities/inclusions
- Lattice parameters
- Defects

PROPERTIES
- Equation of state
- Shear Strength
- Shock Response
- Spall Strength
- Melting

During underground nuclear testing, we took a shortcut from processing to performance

The nuclear threat changed dramatically when Soviet Union was dissolved on Dec. 25, 1991

Reagan-Gorbachev
Reykjavik
Oct. 1986



Berlin - 1989

Soviet Union - 1991

We were threatened more by Russia's weakness than by its strength

U.S. view of 1992 clear and present danger in Russia

- Loose nukes
- Loose nuclear materials
- Loose nuclear people
- Loose nuclear exports

Threat changed from nukes in hands of Soviet government to nuclear assets getting out of the hands of government

U.S. view of 1992 clear and present danger in Russia

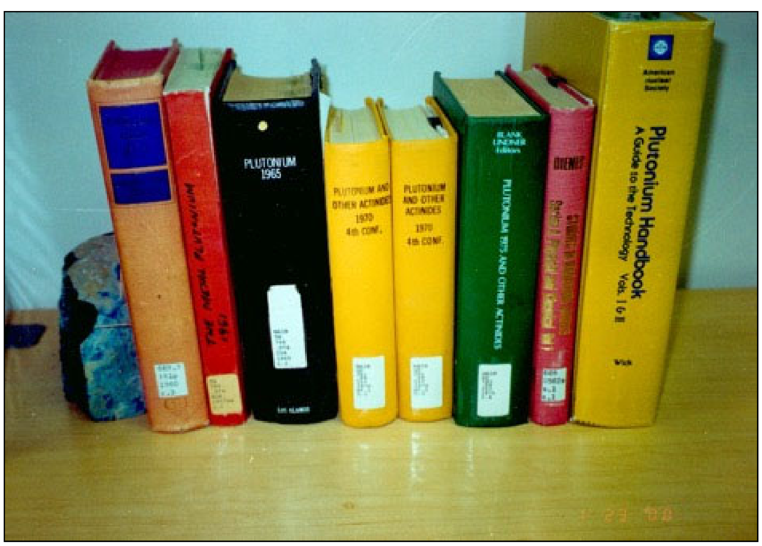
- Loose nukes
  - Tens of thousands nuclear weapons
- Loose nuclear materials
  - ~ 1,400,000 kg fissile materials
- Loose nuclear people
  - Several hundred thousand in nuke complex
- Loose nuclear exports
  - Huge complex, with economy in chaos

It had the making of a perfect nuclear storm

"Doomed to Cooperate"
S.S. Hecker, editor
2016 Bathtub Row Press

Sarov, Russia - Feb. 1992

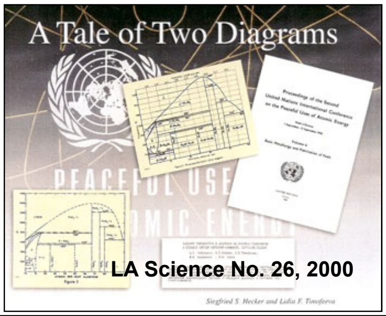
Much of the useful plutonium engineering, materials, and chemistry information relevant to weapons was in the open literature by 1970



End of Cold War opened up collaboration in plutonium research

L. Timofeeva & S. Hecker (2000)

B. Litvinov
E. Kozlov (1998)
L. Timofeeva

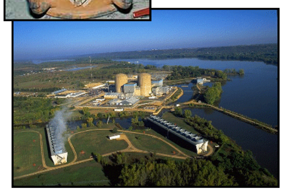


LA Science No. 26, 2000

Nuclear terrorism presents the most urgent challenge

- Nuclear detonation – a real WMD; massive, devastating, no analogue

- Radiological dispersal device – "dirty bomb." A weapon of mass "disruption"



- Radiological sabotage – nuclear facilities. Radiation release concerns

Nuclear weapons or weapons-usable material in the hands of terrorists pose the greatest risk

U.S. plutonium inventories demonstrate magnitude of challenge

- Total U.S. acquisition of plutonium – 111,400 kg
- Total U.S. used
  - Expended in Wartime and Tests 3,400 kg
  - Inventory Differences 2,800 kg
  - Waste (Normal Operating Losses) 3,400 kg
  - Fission and Transmutation 1,200 kg
  - Decay and Other Removals 400 kg
  - U.S. Civilian Industry 100 kg
  - Foreign Countries 700 kg
    - Grand total used 12,000 kg
  - Classified transactions & rounding 100 kg
- U.S. plutonium inventory as of 1994 99,500 kg

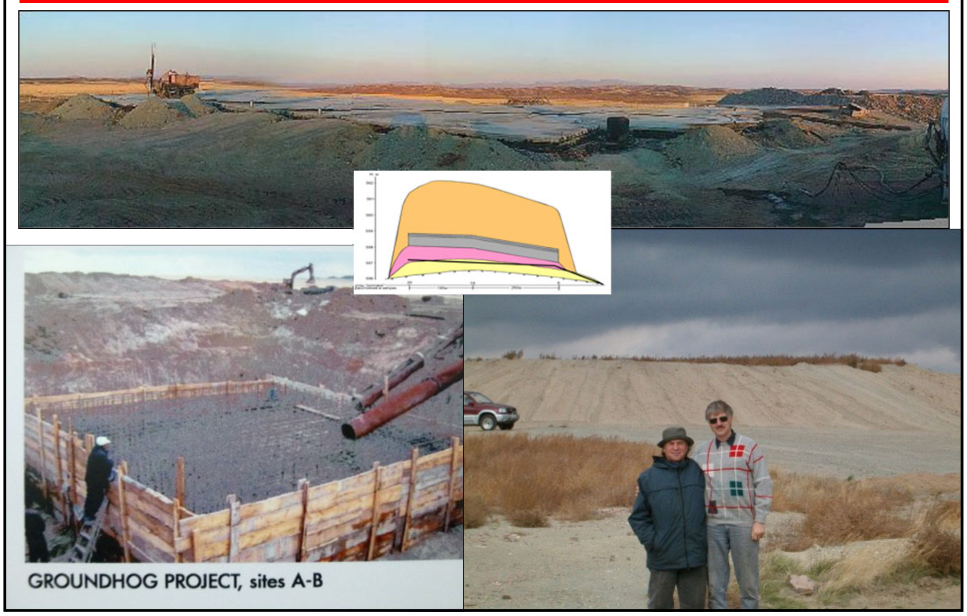
Plutonium: The First 50 Years (DOE: 1995)

Our confidence in the security of the plutonium is only as good as our confidence in the integrity of the safeguards system

Semipalatinsk Test Site – April 19 - 20, 1998

Operation Groundhog – a trilateral success

Russia, United States, Kazakhstan



Plutonium in nuclear energy


Nuclear reactors in Cattenom, France

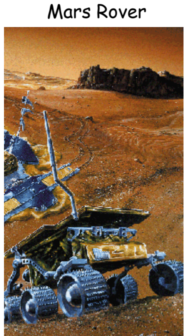
- In uranium-fueled reactors (LWRs), in-grown plutonium accounts for roughly 30 % of the energy production

- Plutonium can also be burned with uranium to fuel nuclear reactors. MOX (mixed oxide) fuel replaces uranium dioxide.
- Plutonium can also be burned in Fast Reactors and bred in Fast Breeder Reactors.
- Plutonium can also be a fuel for accelerator-driven nuclear systems


MOX fuel assembly

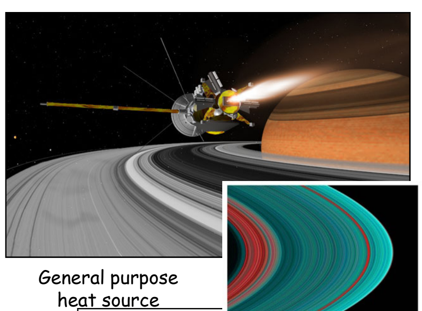
Plutonium radioisotope heat sources use Pu-238

Mars Rover

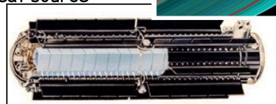



Pu heater to keeps things warm on Mars Rover

NASA's Cassini at Saturn

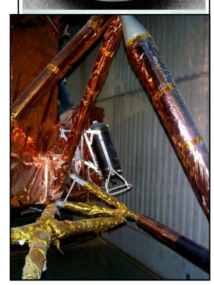


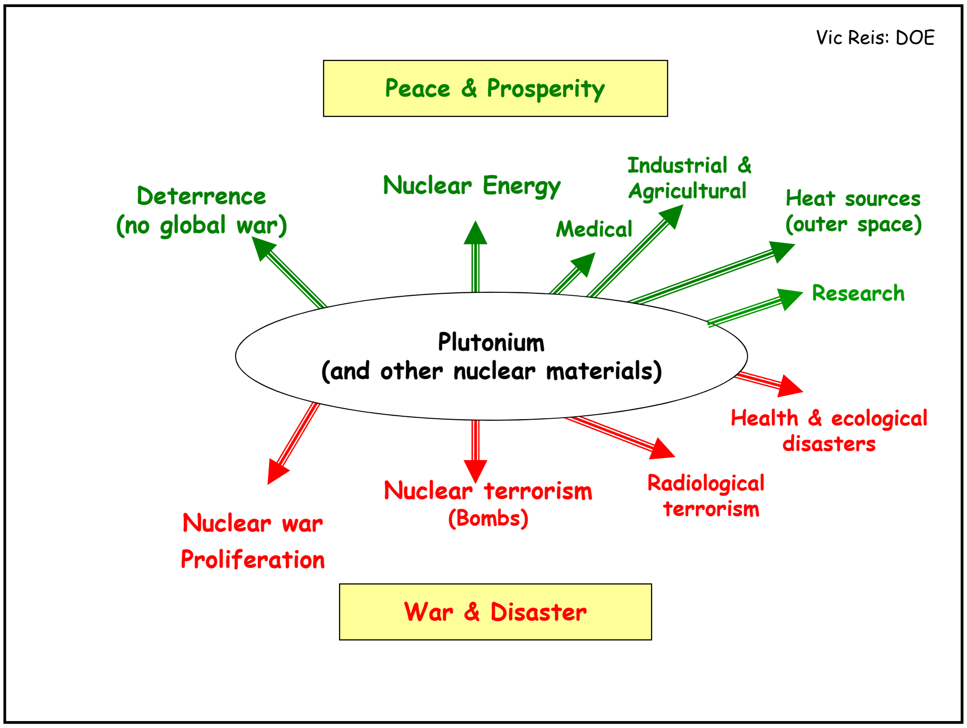
General purpose heat source

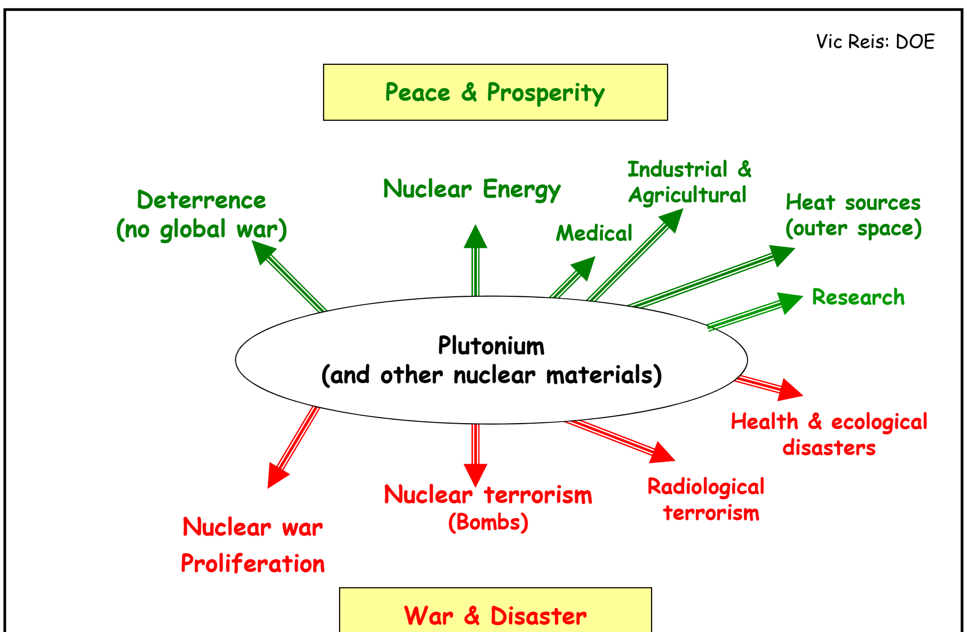



Plutonium heat source

Pu Heart Pace Maker


RTG for lunar science station





We are counting on you to make sure that at the 100th anniversary of MP, we'll be able to say it turned out all right

Physics Underpinnings

James L. Smith

The neutron was discovered in 1932 by James Chadwick. The name neutron was already taken, and so Enrico Fermi changed the name of the other particle to neutrino by using an Italian diminutive ending on neutron. Fermi began using neutrons from radium- or radon-beryllium sources to transmute the nuclei of atoms and was awarded the Nobel Prize in 1938 for creating new radioactive elements.

These are now in great demand as medical isotopes and are produced at LANSCE be diverting some of the proton beam before it reaches its full energy. Fermi thought he had found the element after uranium, but it sure had a lot of funny radiation – fission fragments we know now. In 1938, Hahn and Strassman reported that they had split the uranium nucleus, and immediately after that Meitner and Frisch explained that neutrons and much energy were released, coining the term fission. The cognoscenti immediately understood that a bomb was possible, and the only question was how difficult that might be.

The USA got off to a slow start, but Los Alamos became part of the Manhattan Project in 1943. That same year, Sig Hecker and I were born 29 days apart. My first language was English, and his was German. Radios took minutes to warm up; calculations were done on slide rules; and food was organic because the bad things had not been invented.

There were not important materials discovery during the Manhattan Project. The role of the chemists, metallurgists, and solid-state physicists was to provide the framework for the nuclear physics to play out. Materials had to be made purer and formed into shapes. Here is Larry Litz's notebook page from D-Day. You see that by the time people got to work, it was already on the radio that the invasion of France was underway. You can see that he was worrying about outgassing things and light-metal impurities in his samples. Vern Struebing cast the plutonium for Trinity and Combat. Everyone used induction heating for melting materials, and when Vern showed me how to use one, he had an optical pyrometer with a shoulder strap on it. I had never seen lab equipment with such a strap. It was from the Manhattan Project and was a style for steel mills.

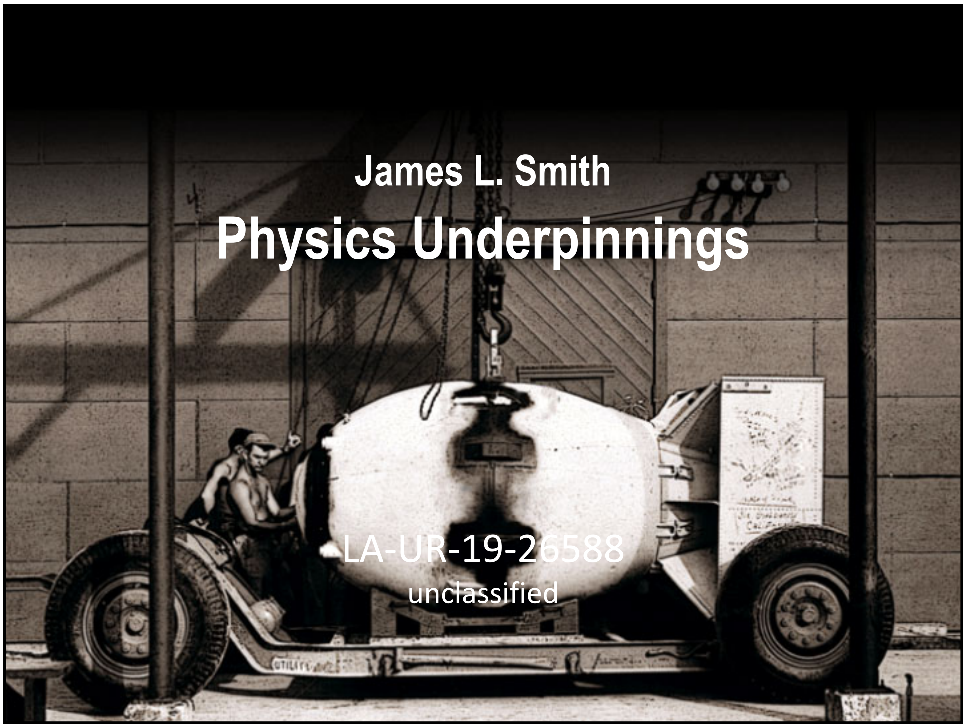
If you arrange the *f*- and *d*-electron series as in the figure, a pattern emerges. While *s*- and *p*-electron solids are simpler to understand, the long filling of the *f* and *d* shells leads to gradual changes in properties as the atoms contract along the series. If the electrons overlap well, they may become superconducting and isolated electrons in a partially filled shell can possess a magnetic moment and order magnetically at low enough temperatures. Thus, the red and blue regions are simple enough, but in the region where the electrons are on the edge between the two states, interesting behavior occurs. The properties are quite sensitive to perturbations such as temperature, pressure, impurities, magnetic fields, and stress. So, the metals have many crystal structures, variable properties, and make sparks when struck. The next figure shows the actinide row that displays these properties well. These are the binary alloy phase diagrams of pairs plotted in a series. The unknown ones, which are my guesses, are shown with cross hatching. This shows the way the melting points plummet; the crystal structures multiply; and then go back to normal behavior as the *f* electrons cross over from bonding to localized.

Strange things can emerge in materials. Consider the compound UBe_{13}. The uranium atoms are well spread out by the harmless beryllium atoms and should possess a magnetic moment. As seen in the plot of magnetic susceptibility, it has a moment above liquid-nitrogen temperature. But, everything else is crazy. The heat capacity of Joules/mole K looks magnetic, but goes superconducting at about 1 K. So the superconducting electrons behave as though their masses were 1000 times larger than normal. They barely want to move even though they are superconducting. This so-called heavy-fermion superconductor and other similar compounds are not completely understood.

In 1987 superconductivity was found above liquid-nitrogen temperature. Edward Teller, co-inventor of the hydrogen bomb and co-founder of Lawrence Livermore National Laboratory, wanted someone to teach him superconductivity. He looked around the two labs and picked me as his teacher. We spent about 100 hours together and became friends. He was a good student. The transition temperatures are now approaching room temperature. I have no doubt they will get to room temperature, but the difficulty will be making this useful. This high-temperature superconductivity is not fully understood yet.

The superconductors are examples of emergent phenomena, namely complex and unexpected behavior arising from simple things. The Gulf Stream is an example from geology. So what does the future hold? Paul Dirac did mathematics describing a Dirac material where the energy is linear in the absolute value on the momentum, unlike energy going as p^2 over 2m. This seems to be quite unphysical. But they have been realized recently in materials, not free space. Here the spin would still give a degeneracy, but it gets better. In Weyl materials only one spin is associated with a particle. I have read that these materials may lead to better computers and that these computers may help us figure out what is going on with over half of the matter in the universe that we cannot see or understand. It is our meeting organizer Alexander “Sasha” Balatsky who wrote this, and so ask him, not me, about this.

Why do we still care about nuclear weapons? We cannot just leave them somewhere because they are radioactive and contain explosives. I do subscribe to the view that their existence has prevented another world war. If we get a bit smarter our costs can be reduced substantially. And as long as we do not resume testing them, they will slowly get less important. A more active plan at eliminating nuclear weapons is far more desirable, but the non-testing default is a minimum possibility.



1930s

The neutron is discovered by James Chadwick in 1932.

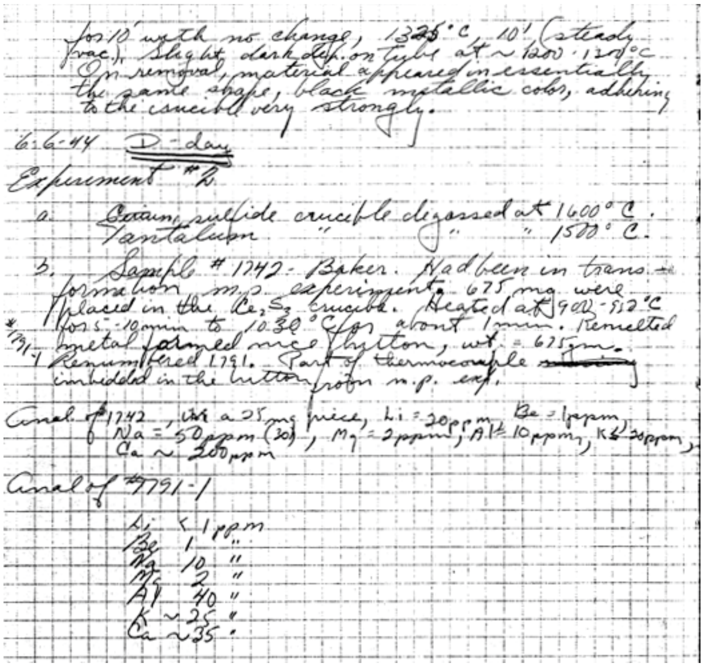
Using neutrons Enrico Fermi made many new isotopes and fissioned ^{235}U without realizing it.

Otto Hahn and Fritz Strassmann discover nuclear fission in 1938.

Lise Meitner and Otto Frisch explain it immediately in 1939.

An atomic bomb becomes feasible, and we fear that Germany will develop it.

Then to 1943.



for 10' with no change, 1325°C, 10' (steady vac.). Slight dark dep. on tube at ~1200-1250°C. On removal, material appeared in essentially the same shape, black metallic color, adhering to the crucible very strongly.

6-6-44 D-day

Experiment #2

a. Cerium sulfide crucible degassed at 1600°C.
Tantalum " " " 1500°C.

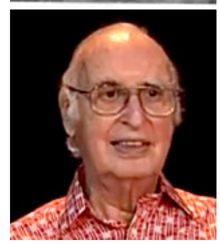
b. Sample #1742 - Baker. Had been in transformation m.p. experiment. 675 mg were placed in the Ce_2S_3 crucible. Heated at 900-950°C for 5-10 min to 1030°C for about 1 min. Remelted metal formed nice button, wt = 675 mg. Renumbered 1791. Part of thermocouple imbedded in the button from m.p. exp.

*1791-1

Anal of 1742, on a 25 mg piece, Li = 20 ppm, Be = 1 ppm, Na = 50 ppm (30), Mg = 2 ppm, Al = 10 ppm, K = 20 ppm, Ca ~ 200 ppm

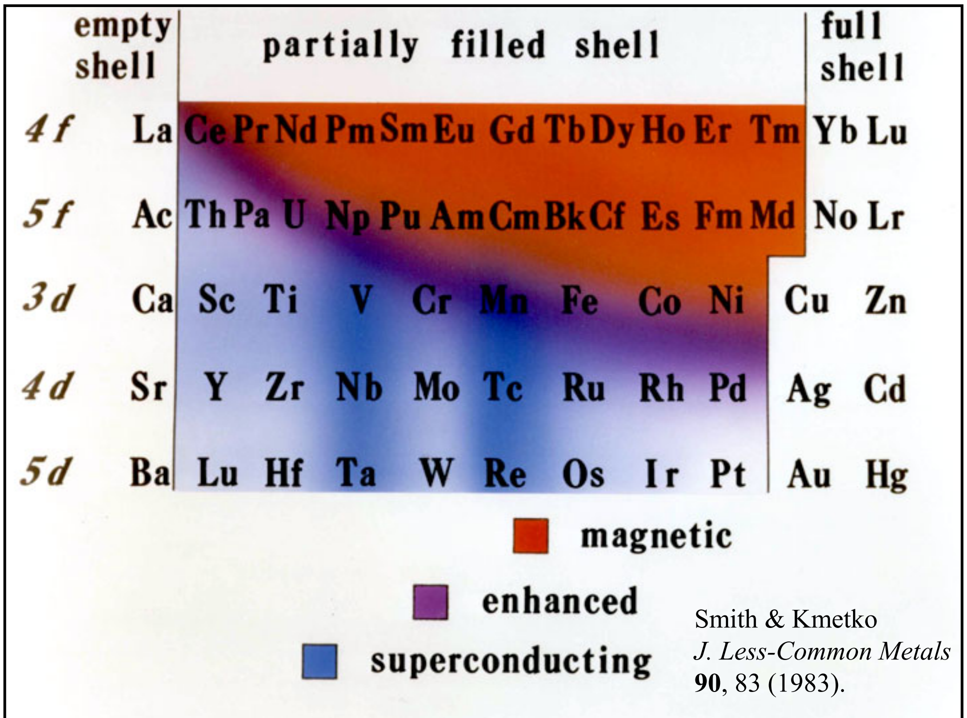
Anal of #1791-1

Li < 1 ppm
Be 1 "
Na 10 "
Mg 2 "
Al 40 "
K ~25 "
Ca ~35 "



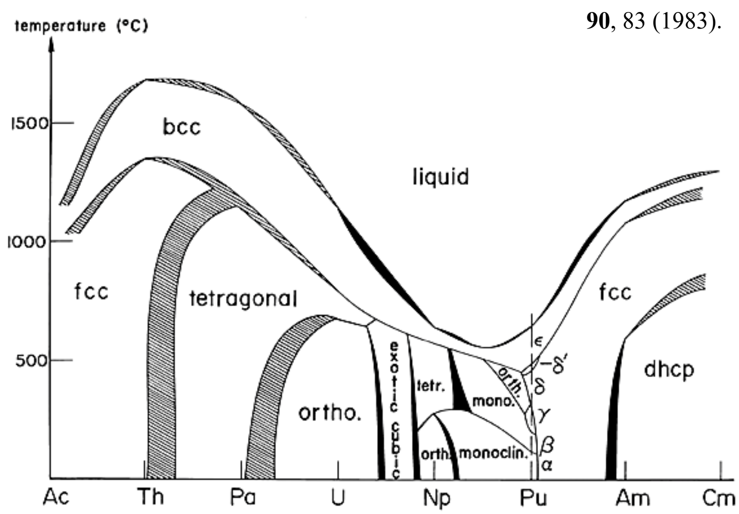
Lawrence Litz

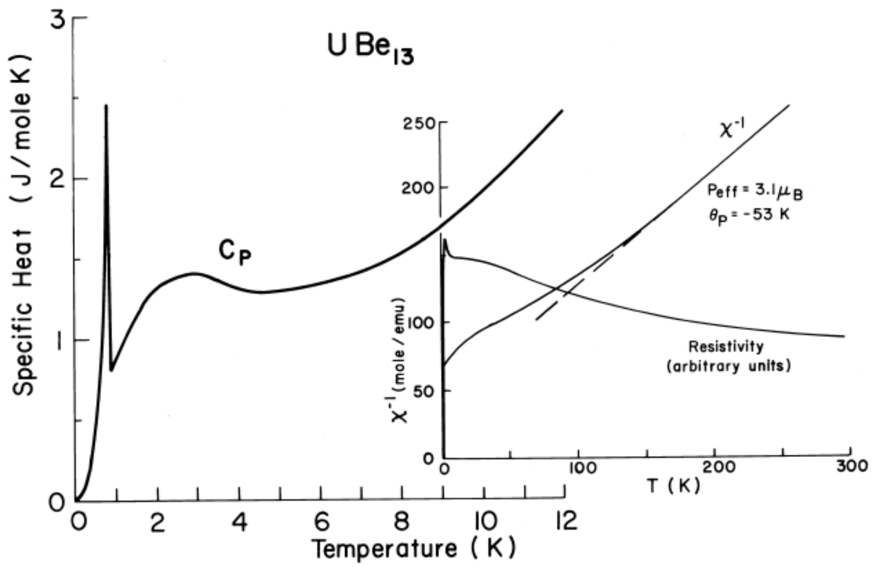
Vern Struebing cast Pu and taught me how to make samples.



Smith & Kmetko
J. Less-Common Metals
90, 83 (1983).

Smith & Kmetko
J. Less-Common Metals
90, 83 (1983).





Ott, Rudigier, Fisk, & Smith
Phys Rev Lett **50**, 1595 (1983)

Here are Edward Teller and me, 23 May 89, Huntsville, AL.

Emergent phenomena

Why do we still care?

Chemistry Challenges for the Manhattan Project and beyond.

David L. Clark, National Security Education Center (NSEC), LANL

Synthesis of Plutonium and demonstration of its fission properties. The important isotope ^{239}Pu was discovered in 1941, as the decay product of ^{239}Np produced with neutrons from a cyclotron. The importance of plutonium comes from its fission properties and its capability of being produced in large quantities. In 1941, Emilio Segre, Kennedy, Wahl and Seaborg bombarded a 1.2 kg sample of uranyl nitrate with 16 MeV neutrons for 2 days. The uranyl nitrate was extracted into diethyl ether, and the ^{239}Np was extracted into an aqueous phase using an oxidation-reduction with La and Ce fluoride carrier. On March 28, 1941, Kennedy, Seaborg, Segre, and Wahl first demonstrated that ^{239}Pu undergoes slow neutron-induced fission with a fission cross section for ^{239}Pu that was approximately 50% greater than that for ^{235}U, agreeing remarkably well with more accurate values determined later. This observation that ^{239}Pu was fissionable with slow neutrons provided the information that formed the basis for the U.S. wartime Plutonium Project of the Manhattan Engineer District (MED) centered at the Metallurgical ("Met") Laboratory of the University of Chicago. Remarkably, the majority of early studies of these elements was carried out under a self-imposed cover of secrecy due to the potential military applications of plutonium, and was not published until after the end of World War II.

Chemistry Challenges. Since only tracer quantities of plutonium existed at the beginning, the first chemistry challenges were to develop 1) a method for the production of plutonium on a large scale, 2) to determine the chemical properties of plutonium so as to develop a method for its chemical separation and purification; and 3) scale up the chemical separations from micrograms to kilograms. Enrico Fermi solved the first problem by demonstrating that uranium would undergo a nuclear chain reaction on Dec 2, 1942. The neutrons produced in the chain reaction would therefore produce plutonium. The solution to the second and third problems came down to determining the chemical properties of plutonium well enough that a large-scale separations plant could be designed to separate plutonium from the enormous quantity of fission products and uranium. Berkeley Professor Glenn Seaborg led a large group of chemists and chemical engineers to solve this problem.

Tracer chemistry precipitation techniques. The key to plutonium separation was the oxidation-reduction cycle, in which plutonium is "carried" in its lower oxidation state(s) by chemical precipitates and not carried when plutonium is present in higher oxidation states. Plutonium therefore becomes separated from the fission products, which don't exhibit these differences in carrying behavior. These carrier techniques had been developed for use with tracer quantities of newly discovered atoms. It was unclear/unknown if these techniques could be scaled up, and actually used in a chemical separations plant. A whole new effort in ultramicrochemistry was developed and led by Burris Cunningham to determine the chemical properties of plutonium because they only had submicrogram quantities at the time. Hundreds of pounds of uranium were bombarded with neutrons at the Washington University cyclotron, and chemically separated down to 2.77 micrograms as the first weighable sample of plutonium on Sept 10, 1942.

The Bismuth Phosphate Process. The Seaborg team had to find a way of separating plutonium in high yield and purity from the many tons of uranium in which plutonium was present at a maximum concentration of only 250-300 ppm. Because of these low concentrations, compounds of plutonium could not be precipitated directly, and any precipitation-separation process had to be based upon coprecipitation with "carriers" for plutonium. Bismuth(III) phosphate was chosen as the carrier. In addition, the highly radioactive fission products had to be separated to less than one part in 10^7 of the original plutonium. This rigid requirement was necessary so that separated plutonium was safe to handle. Without separation from the fission products, the plutonium from each ton of uranium would have more than 10^5 Ci of energetic gamma radiation.

The key to the bismuth phosphate process was the quantitative carrying of Pu(IV) from acid solution by Bi(III) phosphate, and the lack of carrying of Pu(VI) by Bi(III) phosphate. In the process, neutron-irradiated uranium is dissolved in HNO_3, then H_2SO_4 is added to prevent precipitation of uranium. The Pu(IV) is coprecipitated with bismuth phosphate. The precipitate is redissolved in HNO_3, and Pu(IV) is oxidized to Pu(VI). The bismuth phosphate precipitate is then removed and the Pu(VI) stays in solution. Pu(VI) is then reduced back to Pu(IV) and the cycle repeated, but in subsequent cycles, LaF_3 is as the carrier because the volumes are now smaller. At this point, plutonium is sufficiently concentrated that a final purification can take place through precipitation with peroxide without a carrier to produce plutonium peroxide, $Pu(O_2)_2$. The overall decontamination was 10^7. Unfortunately, the process suffers from the batch nature of operations, the large amounts of chemicals used, and large amounts of waste.

After the Manhattan Project – the Cold War Era

PUREX – the game changer. During the Cold War, the PUREX (plutonium uranium redox extraction) solvent extraction process revolutionized plutonium separations. In solvent extraction, the species to be separated is caused to transfer between two immiscible or partially miscible phases, such as water and a nonpolar organic phase. The process works by selectively complexing the actinide species of interest, causing their solubility in water to decrease with a concomitant increase in its solubility in the organic phase. By far, the most important and widely used neutral extractant is the organophosphorus ester, tributylphosphate (TBP). TBP forms complexes with the actinide elements Th, U, Np, and Pu by

$$Pu^{4+}_{aq} + 4\ NO_3^-{}_{aq} + 2\ TBP_{org} \rightleftharpoons Pu(NO_3)_4(TBP)_2{}_{org}$$

$$UO_2^{2+}{}_{aq} + 2\ NO_3^-{}_{aq} + 2\ TBP_{org} \rightleftharpoons UO_2(NO_3)_4(TBP)_2{}_{org}$$

$$HNO_3^-{}_{aq} + TBP_{org} \rightleftharpoons TBP \cdot HNO_3{}_{org}$$

forming inner sphere chemical bonds to the actinide metal atom via the phosphoryl P=O bond. The important reactions for UO_2^{2+} and Pu^{4+} are shown above.

The reactions are equilibrium reactions, and the equilibria can be shifted to the right, increasing the degree of extraction by increasing the concentration of uncomplexed (free) TBP in the organic phase, or by increasing the concentration of NO_3^- in the aqueous phase. The latter is done by adding a salting agent such as HNO_3 or $Al(NO_3)_3$. These extraction equilibria are the basis of the PUREX process, used almost exclusively world-wide in all modern reprocessing of spent nuclear fuel. In the PUREX process, irradiated UO_2 fuel is dissolved in HNO_3 with uranium being oxidized to $UO_2(NO_3)_2$ and plutonium oxidized to $Pu(NO_3)_4$. A solution of TBP in a high boiling organic solvent such as n-dodecane is used to selectively extract the hexavalent $UO_2(NO_3)_2$ and the tetravalent $Pu(NO_3)_4$ from the other actinide and fission product nitrates in the aqueous phase. In second extraction container, the TBP solution is contacted with a dilute HNO_3 solution containing a reducing agent such as ferrous sulfamate, which reduces plutonium to Pu(III), but leaves the uranium as U(VI). Plutonium then transfers back to the aqueous phase leaving uranium in the organic phase. The uranium is stripped from the organic phase using water.

The Hanford PUREX plant was authorized in 1953, and hot operations began in January of 1956. The initial processing rate was 200 MT/U/month. PUREX capacity soared and by 1961, PUREX was processing 800 MT/U/month. Although the PUREX waste-to-product ratio was much lower than other processing plants, the need for waste disposal soared. Hanford responded with many different campaigns to build new waste tank farms to store the highly radioactive waste.

The tank waste legacy. Managing and treating the tank wastes stored in the farms of aging underground tanks at the SRS and at Hanford has been a grand challenge for the EM mission posing the most significant threat to environment, safety and health. The tank farms at Savannah River Site (SRS) and Hanford contained the majority of the DOE tank waste inventory with about 575 million curies of radioactive materials in 91 million gallons of sludge, liquid and solid waste stored in 226 underground tanks. The majority of activity is stored in the SRS tanks (400 million Ci), while the largest volume (53 million gallons) are stored in Hanford tanks (Fig. 1). The costs for managing the tank farms are enormous with about $1 million per day for tanks at SRS and life-cycle costs in the billions of dollars. Estimates for life-cycle costs reach nearly $250 billion with completion of the cleanup of SRS and Hanford tank farms by the latest 2062. Although EM has made significant progress in its cleanup mission, the majority of the tank wastes remain untreated. Only 7 tanks have been emptied and only two have been closed at the SRS; no tanks have been closed at Hanford. Given the enormous task to retrieve, treat and dispose of the large volumes of highly complex and highly radioactive tank wastes opportunities exist to invest in the development of advanced technologies and scientific understanding of tank waste issues that can accelerate the cleanup mission and reduce life-cycle costs.

Savannah River Site. The Savannah River Plant was built and operated as a second production site for plutonium and other nuclear materials producing well over 100 million gallons of radioactive waste stored in underground tanks. The main process used for treating spent nuclear fuel and separating plutonium was a solvent extraction process using tri-butyl phosphate (PUREX). The wastes were made alkaline for storage in the carbon steel tanks producing an insoluble sludge consisting of the actinides and fission products and a supernatant liquid containing the majority of the ^{137}Cs. To date, the SRS underground tanks received about 140 million gallons of radioactive waste, which was reduced to about 36 million gallons by evaporation. The radioactive waste is currently stored in 49 underground tanks containing about 350 million curies of radioactive material. The SRS tanks reportedly contain about 16.9 million gallons of supernate, 3 million gallons of sludge and 16.6 million gallons of salt cake. Twenty-seven of the underground tanks have full secondary containment in compliance with the site's Federal Facility Agreement (FFA). The remaining 22 tanks have only one or partial second containment and, therefore, are considered non-compliant tanks.

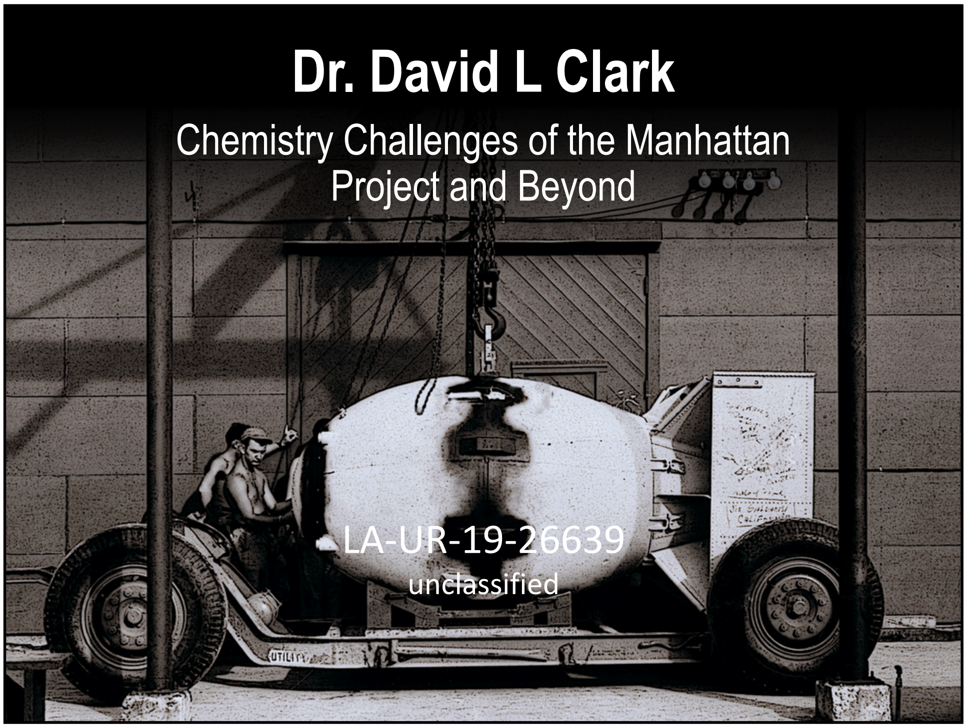
Some of the SRS waste has been treated incorporating the radioactive components into borosilicate glass at the Defense Waste Processing Facility (DWPF) and decontaminated supernate into a cement-based waste form referred to as Saltstone. As of 2016, the DWPF had produced 4,000 glass canisters. In 2008, the DOE entered into a contract with the Savannah River Remediation LLC to accelerate closure of the tanks, and requires that all waste must be removed from all tanks by 2028. Final closure and grouting of the final H-area East Hill tank is scheduled for FY2032.

Hanford Site. The Hanford Reservation was the first industrial-scale plutonium production site in the world including multiple reactors and reprocessing facilities. Plutonium and spent fuel were processed in five reprocessing plants creating large volumes of liquid and solid radioactive wastes. Past waste disposal management involved disposal into the environment and storage in large underground tanks. The Hanford tanks contain 53 million gallons of highly radioactive and chemical waste, only about 10% of the originally generated waste volume. The HLW is stored in 177 single and double shell tanks containing about 175 million curies of radioactive constituents. Nearly 70 single-shell tanks have or are suspected to have leaked up to 1.5 million gallons of waste into the surrounding soil, while none of the 28 newer, double-shell tanks have lost their integrity.

Most of the waste removal and tank closures still have to be done, awaiting the operation of the large Hanford Tank Waste Treatment and Immobilization Plant (WTP). The plant will use vitrification technology, which involves blending the waste with glass-forming materials and heating it to 2,100 degrees Fahrenheit. The molten glass mixture is then poured into stainless steel canisters to cool and solidify. In this glass form, the waste is stable and impervious to the environment, and its radioactivity will safely dissipate over hundreds to thousands of years. The plant is scheduled to begin operations in 2023, but has been historically plagued by setbacks.

Summary Remarks. The creation of atomic weapons and the buildup of the US Cold War nuclear arsenal has left an environmental cleanup legacy of enormous cost and scope—it is the largest environmental cleanup program in the world.

- Through science, technology and engineering, the US has developed innovative solutions and reduced the legacy footprint by 90% to less than 300 square miles to 16 sites in 11 states – (**no other country has done this**).
- Future challenges at Hanford and SRS will give the US experience and technology in HLW treatment, essential components for managing the legacy of future wastes, and spent nuclear fuel (a separate challenge).
- Legacy cleanup is a necessary component in the right sizing and transformation of the US nuclear weapons complex.
- Integration of worker safety and environmental protection into processes and facilities is an essential element of maintaining a modern stockpile.



Chemistry Challenges of the Manhattan Project

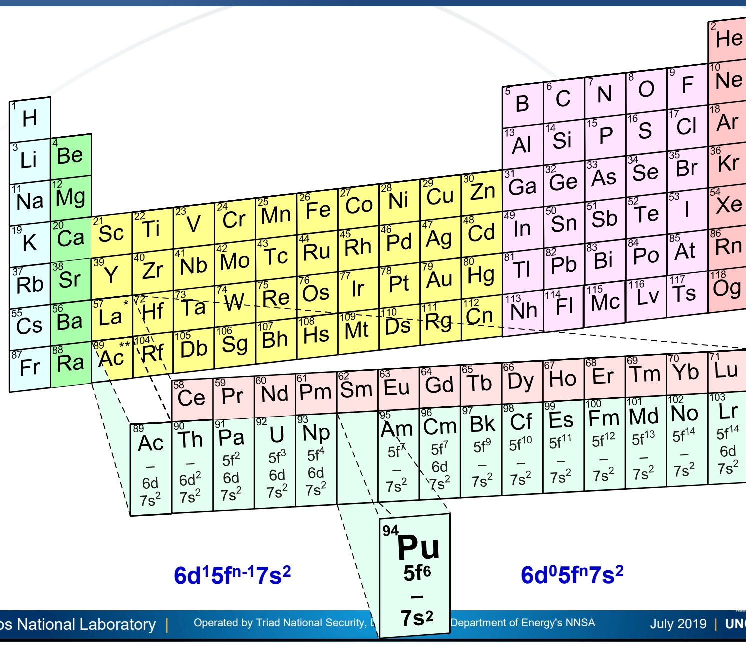
Only a few atoms of plutonium had been discovered in 1941

1) **Find a method for the production of plutonium on a large scale,**
2) **Determine the chemical properties of Pu in order to devise a method for its chemical separation and purification,**
3) **Scale-up the chemical separations from micrograms to kilograms.**
   - Enrico Fermi solved the first problem by demonstrating the first nuclear chain reaction in uranium on Dec 2, 1942.
   - The solution to the 2nd and 3rd problems came down to **determining the chemical properties of Pu** well enough that a large scale separations plant could be designed to separate Pu from the enormous quantity of fission products and uranium.

The Pu Separation and Purification Challenges

- Find a means of separating Pu in high yield and purity from the many **tons of U** in which Pu was present at a **maximum concentration of 250 ppm**.
- Because of this low conc., compounds of **Pu could not be precipitated directly**, and any precipitation-separation process had to be based upon **coprecipitation phenomena**, that is the use of so-called **“carriers”** for Pu.
- The radioactive **fission products** had to be separated to less than **one part in 10^7** parts of Pu originally present. This requirement was necessary in order to make it **safe to handle the Pu**.
- **Without separation** from the fission products, the Pu from each ton of uranium would have more than **10^5 Ci of energetic gamma** radiation associated with it.

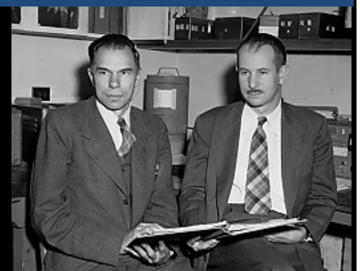
The Actinide Elements



The Discovery of Plutonium-238, 1940

$$^{238}_{92}\mathrm{U} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{238}_{93}\mathrm{Np} + 2\,{}^{1}_{0}\mathrm{n}$$

$$^{238}_{93}\mathrm{Np} \xrightarrow[2.1\mathrm{d}]{\beta^-} \boxed{^{238}_{94}\mathrm{Pu}}\ (t_{1/2} = 87.7\ \mathrm{yrs})$$



Glenn Seaborg Ed McMillan

Seaborg, McMillan, Kennedy, Wahl 1940
Seaborg, Wahl, Kennedy, *Phys Rev*. 1946 *69*, 367

The short half-life of ^{238}Pu was conducive to tracer studies, and allowed for the chemical identification and subsequent separation of other isotopes of Pu.

The Discovery of Plutonium-239 1941

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U} + \gamma$$

$$^{239}_{92}\mathrm{U} \xrightarrow[23.5\mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.36\ \mathrm{d}]{\beta^-} \boxed{^{239}_{94}\mathrm{Pu}}$$

($t_{1/2}$ = 24,110 yrs)

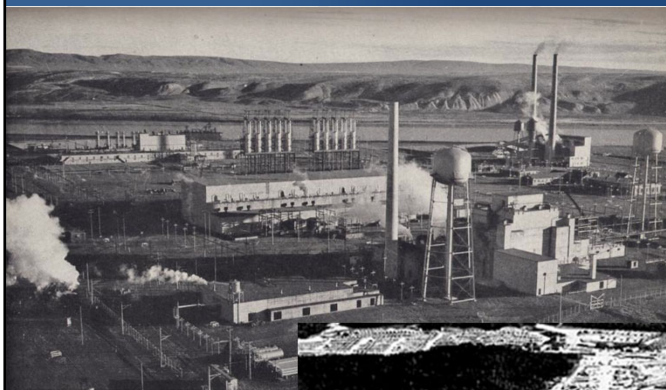
Seaborg, McMillan, Kennedy, Wahl **1941**
Kennedy, Seaborg, Segre, Wahl, *Phys Rev*. **1947**, *70*, 555

"We bombarded …plutonium with …neutrons and produced a half a microgram. We then showed that it underwent fission with slow neutrons, with a cross section about the same as the fissionable isotope of uranium, U-235, **which meant, of course, that it had this potential to be the explosive ingredient for an atomic bomb**".

Art Wahl Glenn Seaborg

"**We kept it secret** voluntarily and when we reported this to the people in Washington, this really became the basis for the plutonium part of the Manhattan Project, the atomic bomb project"

Production of Uranium and Plutonium, 1943

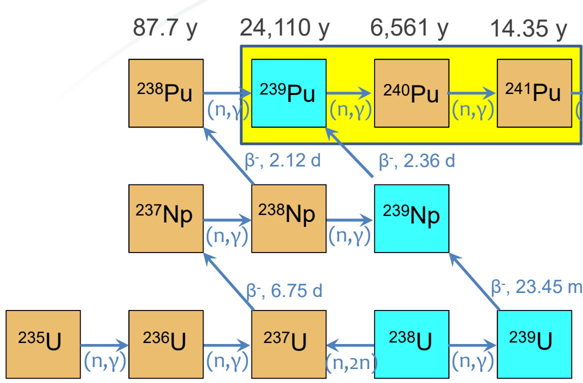


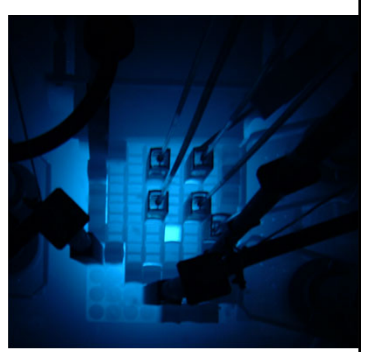
Plutonium (^{239}Pu):
"B" reactor construction began in March of 1943 and came on line in September of 1944!!

Uranium (^{235}U):
The K-25 gaseous diffusion plant, at the time the largest single factory under one roof in the entire world

Preparation of Plutonium

Plutonium Buildup in Nuclear Reactors





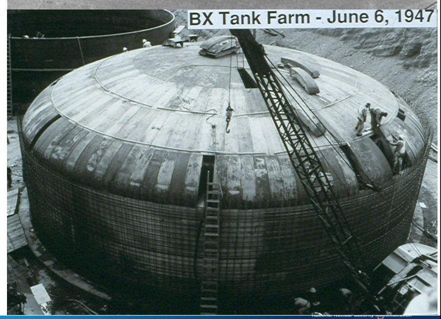
Neutron capture, beta decay

Clark, Hecker, Jarvinen, Neu, *Chem. Act. and Transact. Elements*, Chapter 7, **2006**

Original Plutonium separation: Bismuth Phosphate

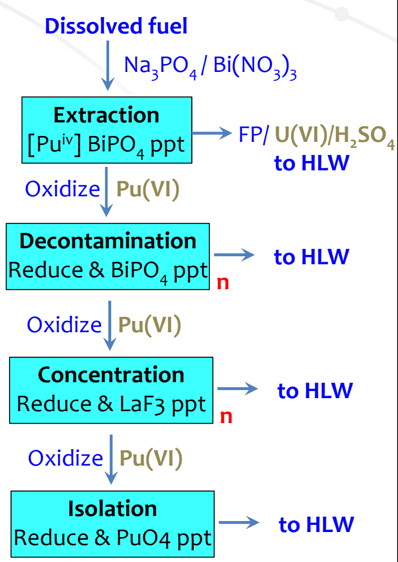
Bismuth phosphate separations chemistry – T Plant 1944

- Seaborg first separated **microgram** quantities (2.77 µg PuO_2) 1942
- Process scaled to **kilogram** production at Hanford in 1944
- ***Scale-up factor of 10^9 !!!***
- 1 - 1.5 tons of fuel per day, whose Pu content was **~ 300 ppm**, resulting **in 300 to 450 g Pu/day**.
- During the 1940s and 1950s the T and B Plants at Hanford generated an average of **30 cubic meters of waste per metric ton** of spent fuel processed
- **U not recovered**



Bismuth Phosphate 'carrier' Process

- n-irradiated U dissolved in HNO_3, then H_2SO_4 added to prevent U(VI) ppt.
- Pu(IV) is coprecipitated with $BiPO_4$.
- Redissolved in HNO_3, oxidize Pu(IV) to Pu(VI).
- $BiPO_4$ removed / Pu(VI) stays in solution.
- Reduce Pu(VI) back to (IV)
- Precipitate Pu(IV) with LaF_3 as 'carrier' due to smaller volumes.
- Precipitate Pu(IV) with H_2O_2 without a carrier.
- Overall decontamination was 10^7.
- Process suffers from **batch nature** of operations - large amounts of chemicals used, - **large amounts of waste**.



Cold War : PUREX process was a game changer

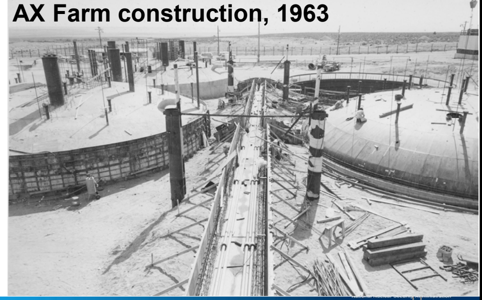
PUREX Plant construction authorized, 1953, operations began in 1956

- Initial processing rate of 200 MT/U month 1956
- Capacity of 800 MT/U month by 1961
- 30% TBP in kerosene or n-dodecane
  - Conducted in a bank of mixer/settler contactors or in a pulsed column

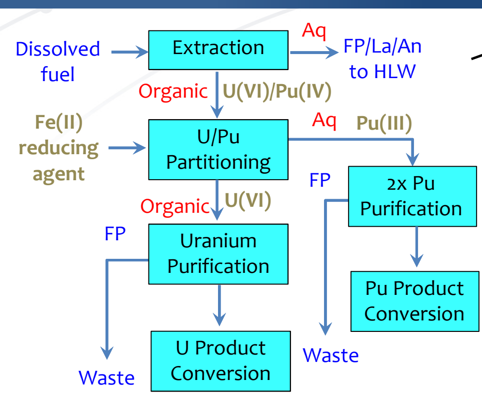
Plant-scale PUREX process performance:

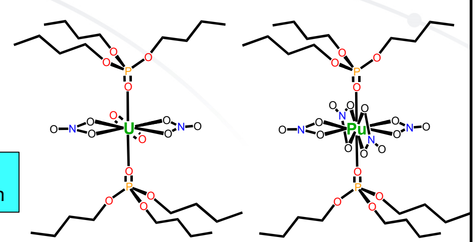
Sep^n of Pu from U	10^6
Sep^n of FPs from Pu	10^8
Sep^n of FPs from U	10^7
Pu & U recovery	99.9%


PUREX construction,1954

AX Farm construction, 1963


A simplified PUREX process





Equilibrium Reactions

$$Pu^{4+}{}_{aq} + 4\ NO_3^-{}_{aq} + 2\ TBP_{org} \rightleftharpoons Pu(NO_3)_4(TBP)_2{}_{org}$$

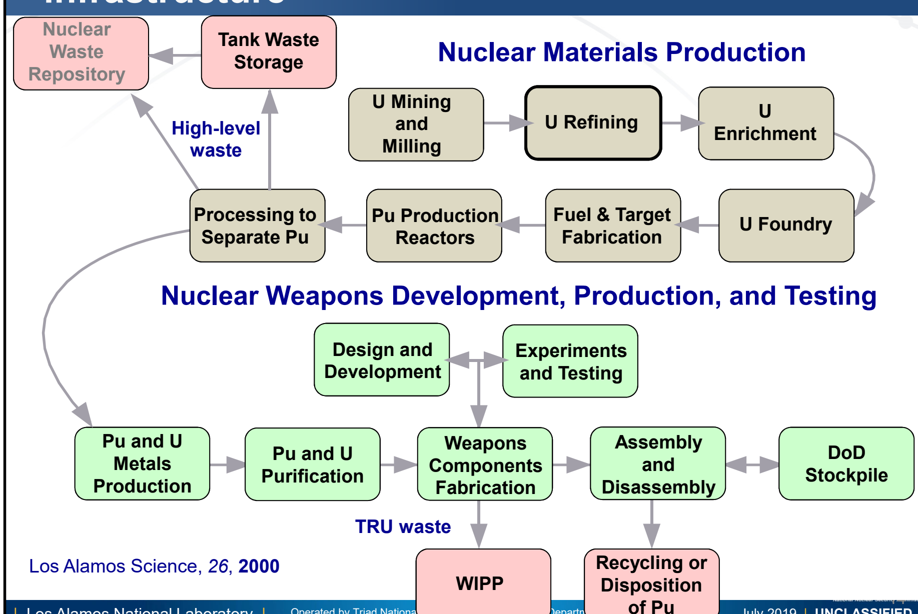
$$UO_2^{2+}{}_{aq} + 2\ NO_3^-{}_{aq} + 2\ TBP_{org} \rightleftharpoons UO_2(NO_3)_4(TBP)_2{}_{org}$$

$$HNO_3^-{}_{aq} + TBP_{org} \rightleftharpoons TBP{\bullet}HNO_3{}_{org}$$

The Cold War - US Nuclear Weapons Complex

- In 1942, the US began to develop atomic weapons technology during the ***Manhattan Project*** to end World War II.
- During the subsequent Cold War period, the US developed a vast research, production, and testing network that came to be known as the ***nuclear weapons complex***.
  - Spanned 107 sites in 35 states covering ca 3100 square miles
- Seventy years of nuclear weapons production and energy research generated
  - Tens of thousands of nuclear warheads and over 1,000 nuclear tests
  - Millions of gallons of high level liquid rad waste stored in aging tanks
  - Hundreds of millions of gallons of liquid rad waste disposed directly into injection wells, trenches, buried drums
  - Millions of cubic meters of solid radioactive wastes
  - Thousands of tons of spent nuclear fuel and special nuclear material
  - Huge quantities of contaminated soil and groundwater

US Nuclear Weapons Cycle required a massive infrastructure



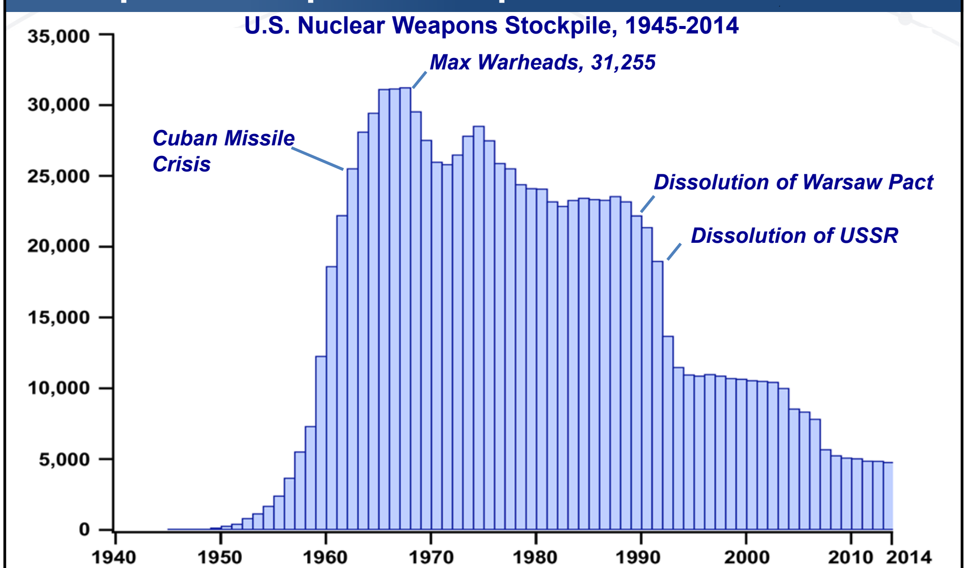
Los Alamos Science, *26*, **2000**

US Nuclear Weapons Complex at the height of its production capacity

Los Alamos Science, *26*, **2000**

| Los Alamos National Laboratory | Operated by Triad National Security, LLC for the U.S. Department of Energy's NNSA July 2019 | **UNCLASSIFIED** | 15

An enormous Cold War buildup of the US nuclear stockpile drove plutonium production



Dept. of State: Transparency in the U.S. Nuclear Weapons Stockpile, April 27, 2015

| Los Alamos National Laboratory | Operated by Triad National Security, LLC for the U.S. Department of Energy's NNSA July 2019 | **UNCLASSIFIED** | 16

Dramatic and turbulent changes at the end of the Cold War

- The dissolution of the Soviet Union, and the unprecedented changes in geopolitics that followed
- The cessation of nuclear testing
- The beginning of Stockpile Stewardship
- Establishment of the US-Russia lab-to-lab, and nuclear materials control and accountability programs
- The establishment of the DOE Environmental Management program (1989) to clean up the radioactive legacy of the Cold War.
- A new generation of scientists & engineers entered the nuclear weapon's complex workforce

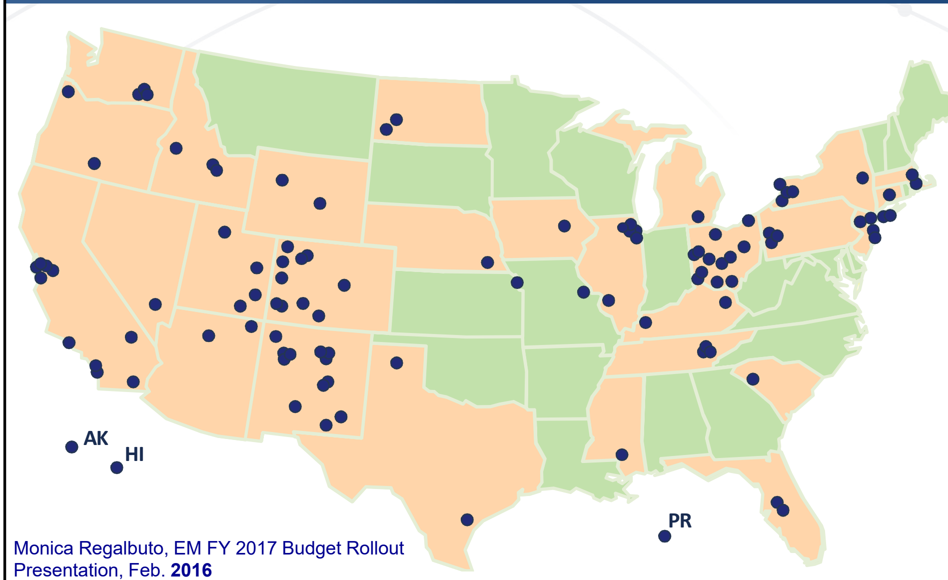
https://energy.gov/em/office-environmental-management

The Post Cold War saw a transition from nuclear weapons production to environmental cleanup

- The DOE Environmental Management program was created in 1989 to clean up the radioactive legacy of the Cold War.
- Early progress included significant first time actions which had never been accomplished before anywhere in the country, including:
  - Starting vitrification of liquid rad waste at the Savannah River Site (SRS) and West Valley Demonstration Project (WVDP);
  - Licensing the nations nation's first deep geologic repository -- the Waste Isolation Pilot Plant (WIPP);
  - Repackaging, transporting and disposing of transuranic (TRU) waste in the Waste Isolation Pilot Plant (WIPP);
  - Cleaning and closing liquid waste tanks at SRS, WVDP, INL, and the Office of River Protection (ORP);
  - Deactivating the Plutonium Uranium Extraction Plant (PUREX).

https://energy.gov/em/office-environmental-management

In 1989, the weapons complex had 107 contaminated sites in 35 states, spanning 3,100 square miles



Monica Regalbuto, EM FY 2017 Budget Rollout Presentation, Feb. **2016**

Early accomplishments included the accelerated cleanup and closure of three major sites

- Rocky Flats in Colorado and Fernald Feed Materials Production Center and the Mound Site in Ohio.
- The cleanup at Rocky Flats constituted the largest environmental cleanup project in the United States at that time.
  - completed 14 months ahead of schedule, $500 million under the contract ceiling, life-cycle cost savings of $20.5 billion.
- Fernald was a landmark success, saving $7.6 billion of life-cycle cost and cutting the schedule by 12 years.
- Fernald and Rocky Flats, are now recreation and wildlife areas, while Mound is an active industrial and technology park.

Rocky Flats 1995

Rocky Flats 2005

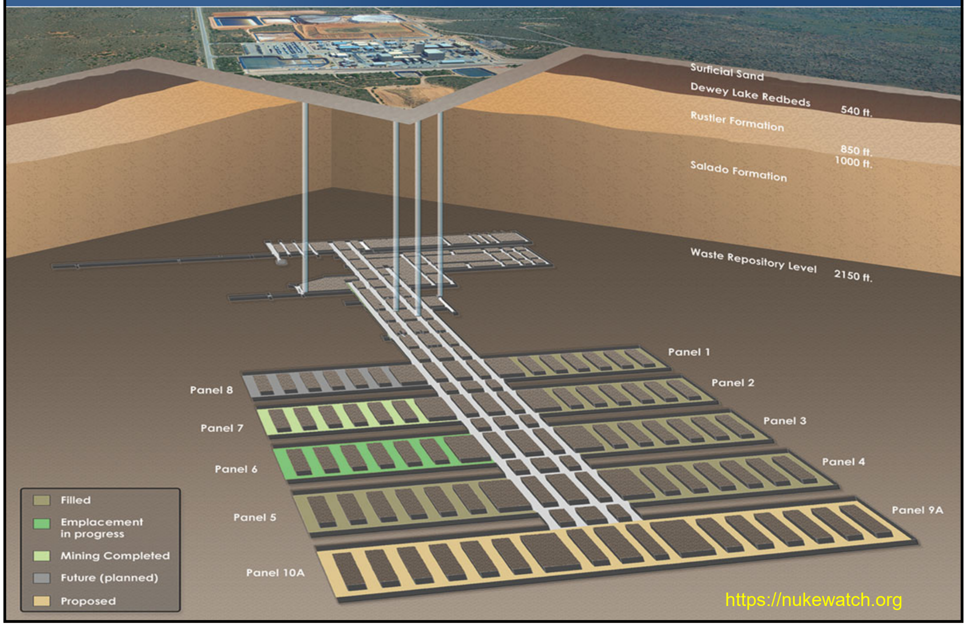
Demolished K-25 Building at Oak Ridge site, once the world's largest building under a single roof

Opened the Waste Isolation Pilot Plant (WIPP) for transuranic (TRU) waste

- Deep geological repository – operational in 1999
- 16 mi^2 near Carlsbad, New Mexico
- Disposal rooms mined 2,150 feet underground in a salt formation
- 20 year effort to make scientific case
- Licensed to permanently dispose of transuranic radioactive waste for 10,000 years
- >12,500 shipments, 96,300 m^3 (178,500 containers) waste received by July 2019
- Estimated to continue accepting waste for 25 - 35 years for total cost of $27 billion (2016 dollars)

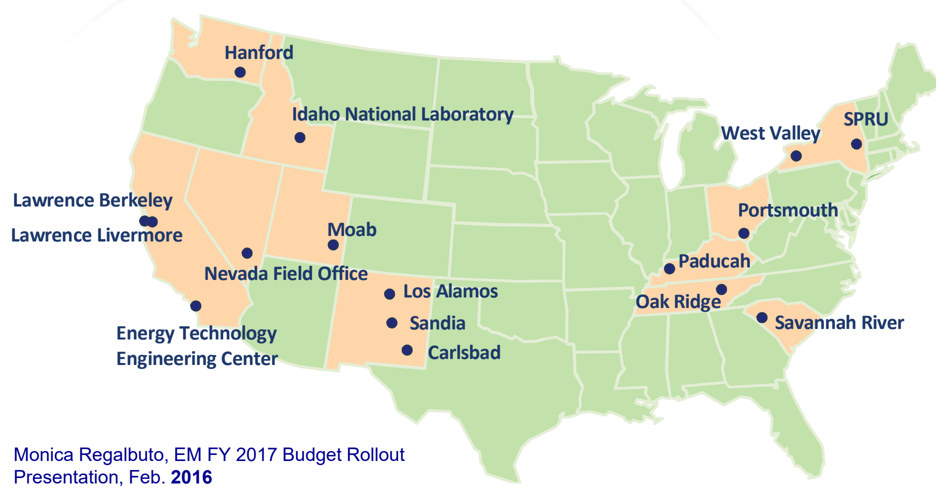
Physics Today 52.5 (1999)

Waste Isolation Pilot Plant



By 2017, DOE had reduced its footprint by 90% to less than 300 square miles to 16 sites in 11 states

While great progress has been made, the remaining sites will be difficult!



Monica Regalbuto, EM FY 2017 Budget Rollout Presentation, Feb. **2016**

Massive amounts of high level radioactive wastes (HLW) were generated from plutonium

- US stored high level radioactive wastes (**HLW**) in shielded, underground tanks
- SRS and Hanford tanks contain 575 million curies in 91 million gallons of sludge, liquid and solid waste stored in 226 underground tanks.
- The costs for managing the tank farms are enormous with about $1 million per day for tanks at SRS..
- Estimates for life-cycle costs reach nearly $250 billion with completion of the cleanup of SRS and Hanford tank farms by 2060-2070.

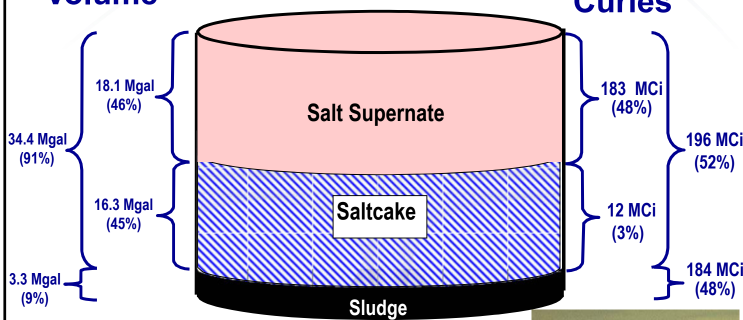
Environmental management technical expert group (EM-TEG). EM tank waste strategy review, Los Alamos National Laboratory, Report LA-UR-11-02972, (**2011**)

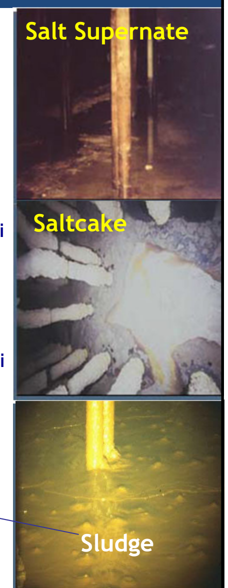
Tank Waste

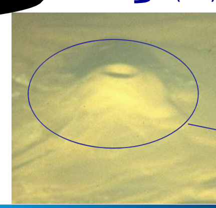
Tank waste characteristics

Example: SRS Inventory

Volume **Curies**







37.7 Million Gallons (Mgal)

Inventory values as of 2008-12-31

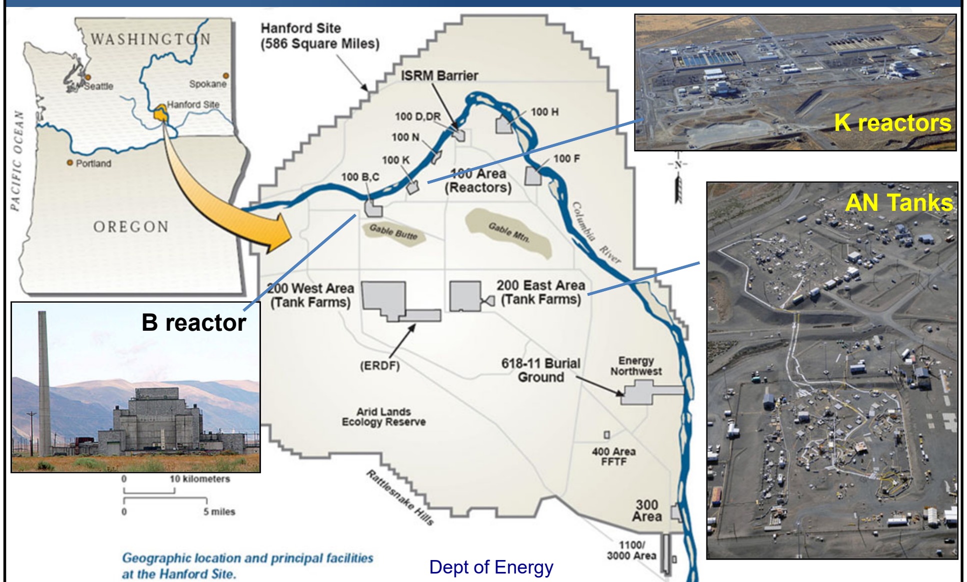
National Research Council, **2006**, ISBN: 0-309-65955-8
EM-TEG Report LA-UR-11-02972, (**2011**)

Defense Waste Processing Facility (DWPF)

Savannah River Site – the DWPF receives waste for processing from H Tank Farm. The waste is "vitrified" and poured into stainless steel canisters that are sealed and decontaminated.

DWPF delivered its 4000th cannister in 2016.

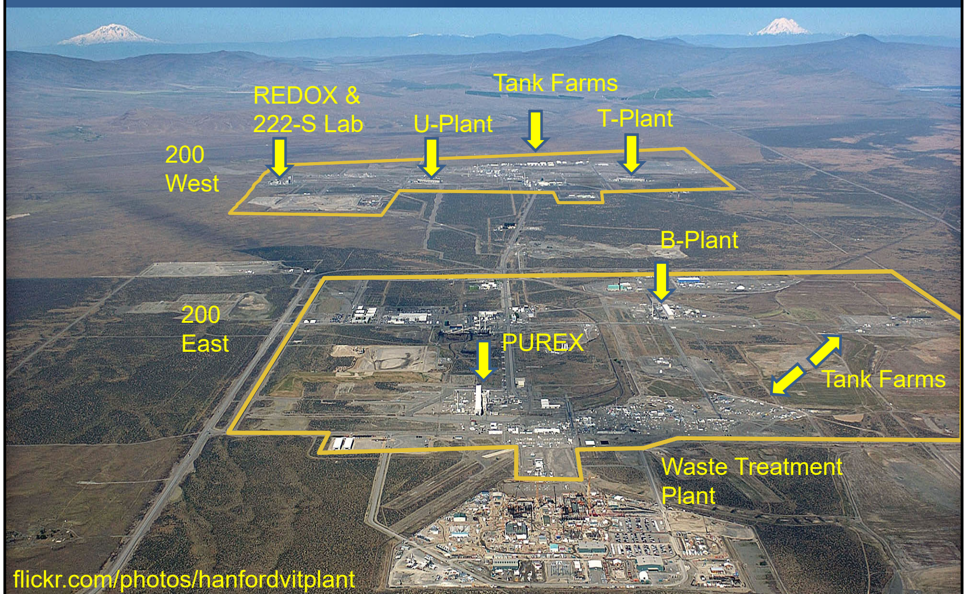
Hanford Site



Hanford Site

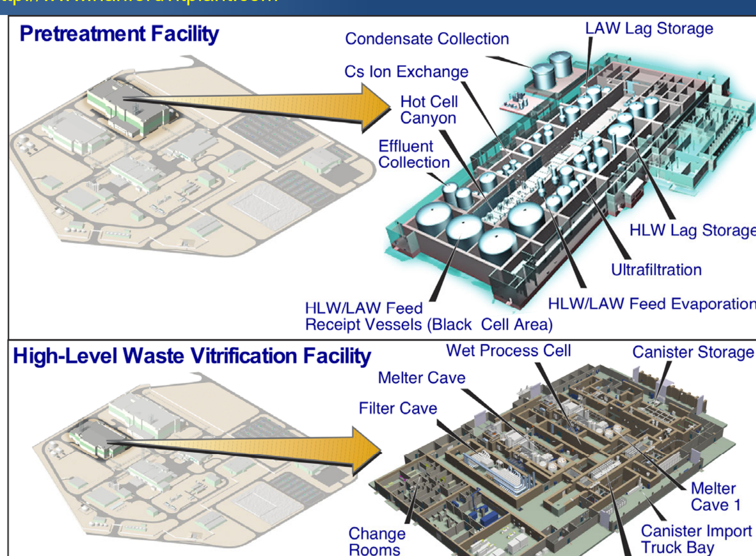
- 586 square mile site
- 9 plutonium production reactors
- 5 plutonium processing plants
- Produced 64 metric tons of plutonium
- Released 725,000 Curies of I-131
- Generated 56 million gallons of radioactive wastes - now stored in 177 underground tanks on the Hanford Site
- 25 million cubic feet of solid radioactive waste
- 200 square miles of contaminated groundwater

Hanford Site today



Waste Treatment & Immobilization Plant (WTP)

http://www.hanfordvitplant.com



WTP fact sheets. **2016**, TP1601_01

Waste Treatment & Immobilization Plant (WTP)

222-S Analytical Laboratory Complex

True costs for WTP are unclear, but growing

- The WTP's approved total project cost is $12.3 billion, but DOE Office of Environmental Management capital project performance reports acknowledge that it will exceed this cost – current estimate is $17 billion to resolve technical issues

In addition

- Low Activity Waste Pretreatment System could range $243 - $375 million
- Tank Waste Characterization and Staging Facility could range $390-$690 million

Hanford Waste Treatment, **2018**, GAO-18-241
Hanford Waste Treatment, **2015**, GAO-15-354
Tri City Herald, Dec 16, **2016**

The scope of the US environmental cleanup work is staggering

- From 1948 to 1996 the United States spent approximately $253 billion (in *2016 dollars*) producing nuclear weapons materials at facilities across the country.
- Over $164 billion has been spent to date in pursuit of environmental cleanup
- 91 of the 107 major sites has been completed, cleanup of 16 difficult and high-risk sites remains.
- The remaining work represents some of the most complex and technically challenging cleanup efforts anywhere in the world.
- In 2018, DOE estimated that the cost to complete the work could cost as much as $377 billion, and take until 2075.

- Stephen I. Schwartz, ed., *Atomic Audit: The Costs and Consequences of U.S. Nuclear Weapons Since 1940* (Brookings, 1998), p 561.; 2016 equiv calculated from Bureau of Labor Statistics bls.gov
- GAO-19-460T, **2018;** GAO-19-223, **2019**
- DOE FY 2016 Congressional Budget Request, DOE/CF-0111 vol 5, **2016**
- Secretary of Energy Advisory Board - Task Force on Technology Development for Environmental Management, **December 2014**

Final thoughts

- The creation of atomic weapons and the buildup of the US Cold War nuclear arsenal has left an environmental cleanup legacy of enormous cost and scope—it is the largest environmental cleanup program in the world.
- Through science, technology and engineering, the US has developed innovative solutions and reduced the legacy footprint by 90% to less than 300 square miles to 16 sites in 11 states – (**no other country has done this**).
- Future challenges at Hanford and SRS will give the US experience and technology in HLW treatment, essential components for managing the legacy of future wastes, and spent nuclear fuel (a separate challenge).
- Legacy cleanup is an necessary component in the right sizing and transformation of the US nuclear weapons complex.
- Integration of worker safety and environmental protection into processes and facilities is an essential element of maintaining a modern stockpile.

From Manhattan to Nonproliferation: What will be the US role in the future nonproliferation?

Galya Balatsky, Intelligence & Systems Analysis, LANL and Parrish Staples, Staples Science & Policy Consulting

To date, the established rules, regulations and international consensus on non-proliferation allow overcoming a variety of issues related to the proliferation of nuclear weapons and nuclear terrorism. Looking into the future, will the US remain a leader in non-proliferation and other security-related areas when the interest in US civilian nuclear projects has been diminishing? With growing global populations comes the growing need for energy. With concerns over climate change, many countries consider nuclear energy as a preferred way to proceed with meeting their energy needs. The countries with desires for nuclear technologies and nuclear produced energy have a right to develop them but they need to do it in a peaceful, safe and secure manner. The challenge is how to introduce and implement sophisticated nuclear technologies in new comer countries, those lacking well-established industrial bases. How best to ensure nuclear technologies are proliferation-resistant? It is important to be proactive and flexible.

The power of nuclear weapons became known after Hiroshima and Nagasaki, and the US leadership was concerned this information may end up in the wrong hands. President Truman signed the McMahon Act in 1946, and the Atomic Energy Act that "conserves and restricts the use of atomic energy for the national defense," came into force. In spite of this policy of secrecy, the knowledge was spreading: USSR tested its first atomic bomb in 1949 and then in 1952 Great Britain performed their test. Under these circumstances, the decision was made to adopt a policy of controlling nuclear information through cooperation and the program "Atoms for Peace" was born and the International Atomic Energy Agency (IAEA) was established in 1957. The IAEA was mandated "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the word" and ensure that it is not used "to further any military purpose."

Nonproliferation efforts were later enhanced by the adoption of the Non Proliferation of Nuclear Weapons Treaty (NPT) which came into force in 1970. The Treaty affirmed the benefits of peaceful applications of nuclear technology. The NPT obliged the nuclear-weapon states not to transfer nuclear weapons nor other nuclear explosive devices to any recipient, as well as not to assist nor encourage non-nuclear weapon states to manufacture or acquire nuclear weapons or nuclear explosive devices. It also places obligations on non-nuclear weapon states not to receive nuclear weapons or other nuclear explosive devices, and in addition not to manufacture nor acquire nuclear weapons or other nuclear explosive devices and not to seek or receive assistance for such. In addition, the NPT requires non-nuclear weapon states to accept safeguards, administered by the IAEA, and defines nuclear-weapons states.

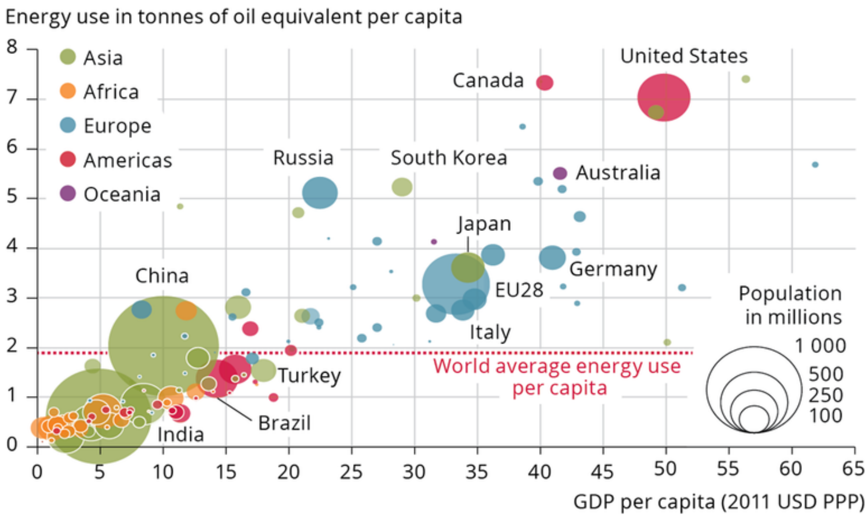
Civil nuclear energy activities rely on facilities and technologies that can also be used in nuclear weapons programs. The main goal of Safeguards is to monitor and verify that states do not divert materials to nuclear weapons programs. Currently, the IAEA has comprehensive safeguards agreements with 175 states and more than 3,000 verifications were performed in 2018.

Over the years, Safeguards were strengthened and other international instruments were added to enhance nuclear safety and security globally. The Nuclear Suppliers Group was established in 1974. The events of 9/11 brought the security of radioactive sources into focus and required countries to address the nuclear terrorist threat. The administration of President Obama held Nuclear Security Summits to improve the security of nuclear materials and generate stronger international support for nuclear security.

Multiple events shaped the development of the current safety and security framework. There were successes, for example, the removal of nuclear weapons from the newly independent countries of Ukraine, Belarus and Kazakhstan and their declaration as non-nuclear weapon states. There were misses, for example, the extended proliferation network set by A.Q. Khan of Pakistan that operated globally for years undetected.

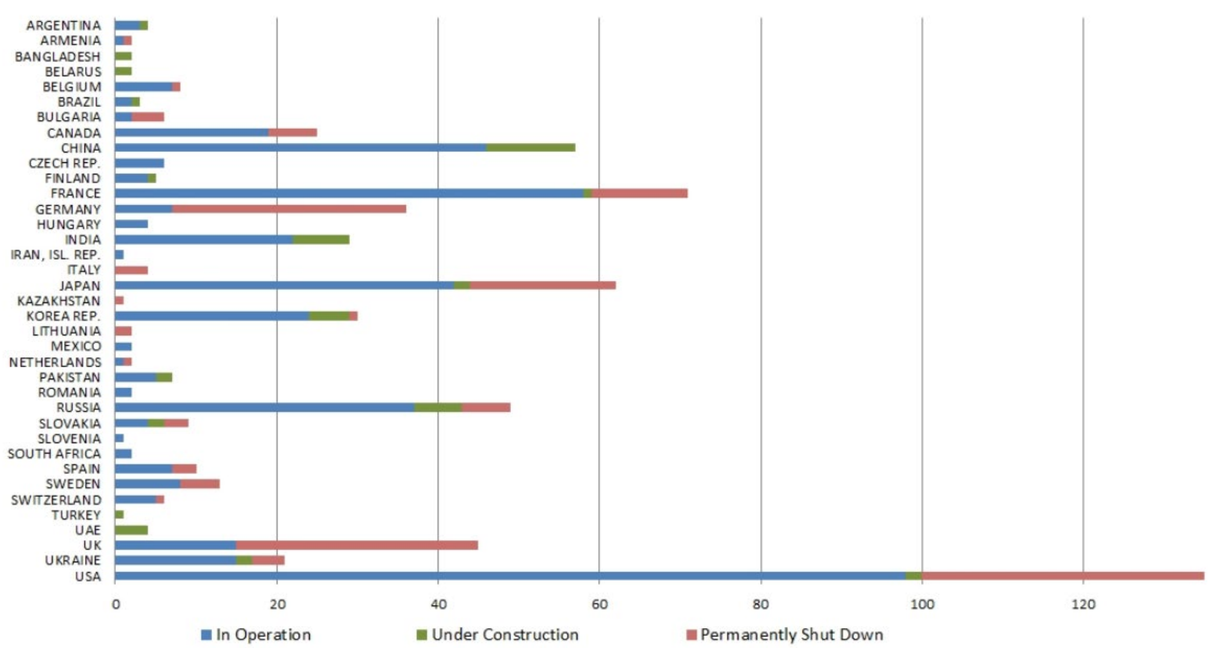
Other events changed the public perception of the benefits and risks of nuclear technologies and impacted policies; accidents like Three Mile Island, Chernobyl and Fukushima made some of the public averse to nuclear energy production, which caused governments in these countries to doubt the future of nuclear projects or abandoned nuclear energy generation completely. Many developing countries need to increase their energy production in order to grow their economy and improve the well-being of their populations. The need for stable power will continue to grow in the future, especially in the South East Asia.

Per Capita Energy Consumption vs. Per Capita GDP, 2011:



The US domestic policies have been affected by public views. The US, the country with the largest number of nuclear power reactors seems to no longer view nuclear power production in their future; the reactors are aging and not many new nuclear reactors are being considered. The US adopted the Nuclear Nonproliferation Act (NNPA) in 1978 due to concerns of uncontrolled sales of nuclear fuel cycle technologies and ongoing efforts to use plutonium in civilian nuclear programs. Since adoption, this Act placed limitations on domestic research and development and on international trade. Over the years, there has been a decline of nuclear scientists and engineers and the number of research programs in the US.

Number of Power Reactors by Country and Status, IAEA, 2018:



The US has been a leader in many nonproliferation activities and provides support to strengthen the nonproliferation regime. It is a dominant funding source for IAEA and initiated and implemented a number of efforts to strengthen the security of nuclear materials.

Non-proliferation, nuclear threat reduction and highly enriched uranium minimization.

In the late 1970's, aligned with the direction of U.S. if not global nuclear efforts, the Reduced Enrichment for Research and Test Reactors (RERTR) program began. The RERTR program enjoyed moderate success and was supported by strong policies within the U.S. government. The most significant is the NRC regulation for U.S. research and test reactors that stipulate that if a low enriched uranium fuel (LEU) (where the ^{235}U isotopic content is less than 25%) and funding is available that the reactor must convert to LEU fuel. Federal Register / Vol. 51, No. 37 / Tuesday, February 25, 1986 / Rules and Regulations, NUCLEAR REGULATORY COMMISSION, 10 CFR Part 50, Limiting the Use of Highly Enriched Uranium in Domestically Licensed Research and Test Reactors.

The U.S. was also an exporter of uranium for use in both foreign research reactors as well as for medical isotope production. The "Schumer Amendment" to the Energy Policy Act of 1992, specifies additional conditions that must be met before highly-enriched uranium (HEU) can be exported from the United States. The U.S.S.R. had a similar uranium export programs for the supply as well as similar efforts to convert those reactors to a lower enrichment of uranium, specifically 36%. It should be noted that the International Atomic Energy Agency (IAEA) specifies that uranium with an isotopic enrichment of 20% or higher be categorized as HEU, and that there are more stringent safeguards and security requirements applicable for a state to possess that material.

The RERTR program staff would provide technical support to facilities interested in obtaining regulatory approval for conversion to LEU fuels. The RERTR program would also work to develop and test advanced replacement LEU fuels that could be used in the conversion of process. Moving into the 1990's the RERTR program began to experience technical difficulties with their latest high-density LEU fuel development program, as well as the program seemed to lose financial support of the government, making it difficult to fully support the LEU conversion process. In addition, the RERTR program was experiencing a significant amount of resistance from the medical isotope production community regarding conversion to LEU material, primarily based on arguments that conversion to LEU target material would be costly to refurbish the production lines, inefficient due to less ^{235}U content and would have an unknown regulatory approval process.

The terrorist attack on September 11, 2001 significantly changed the landscape for nuclear material threat reduction and clearly demonstrated the risk of nuclear material in civilian commerce as well as the risk of non-proliferation from non-state entities. The RERTR program was merged into a group of complimentary nuclear and radiological threat reduction programs coordinated out of DOE/NNSA headquarters and was known as the Global Threat Reduction Initiative (GTRI). The co-location of the programs, the political attention and subsequent funding dramatically increased the rate of conversion of civilian research reactors, both domestically as well as internationally. One of the first actions that the GTRI program implemented was a conversion program of all of the remaining U.S. HEU fueled research reactors that had a LEU fuel available. This effort had two main purposes, to remove the HEU from civilian use, and to demonstrate the commitment and leadership to all other countries that used, possessed or supplied HEU fuel for civilian commerce.

Two efforts from the GTRI continue today that deserve mention here in part to their broad societal impact, as well as continued relevance to non-proliferation and nuclear threat reduction priorities. The first is what is known as the "mo-99" program, so named for the parent isotope that provides technetium-99, which is the workhorse of the nuclear medicine industry and is used globally in ~100k procedures daily. The second is the miniature neutron source reactor (MNSR) conversion program, that provides a forum via the IAEA for dialogue and discussion among the participant countries (China, Ghana, Iran, Nigeria, Pakistan and Syria) of the programmatic issues for the regulatory approval of the conversion of their respective MNSR reactor, the procurement of the LEU fuel and manufacture of the replacement core, as well as the disposition of the spent HEU core originally in the MNSR.

For the in-depth details and story of the complexities of the Mo-99 program, the interested reader is directed first to the publications produced by the U.S. National Academies of Sciences, Engineering, and Medicine, and then to the annual reports published by the Organization for Economic Cooperation and Development- Nuclear Energy Agencies High Level Group/Medical Radioisotopes.

Several of the MNSR conversion program participants have been immersed in wars, U.N. violations for nuclear activities and protracted trade and sanction discussions. It can be imagined that the MNSR conversion program, implemented with the UN/IAEA oversight provides an opportune forum for discussion among the parties. Even with the difficulties facing this group the MNSR conversion program has several significant accomplishments. The MNSR IAE, operated by the China Institute of Atomic Energy in Beijing, which first reached criticality in 1984 was converted to LEU fuel in 2016 as a result of a cooperative project between China Atomic Energy Authority (CAEA) and the U.S. Department of Energy. Ghana's Chinese-origin MNSR converted to LEU fuel in 2017, is the first reactor of this type to be converted outside of China, establishing this cooperative effort as a model for similar cooperation on future MNSR conversions. The conversion to LEU fuel and removal of highly enriched uranium (HEU) fuel from Nigeria's research reactor in early 2018, resulted in all 11 research reactors in Africa being operated on low enriched uranium (LEU).

Outline: What will be the US role in the future nonproliferation?

- Atoms for Peace
- Collapse of USSR, A.Q. Khan
- Nuclear Safety and Security framework
- Nuclear Energy worldwide
- Challenges for the Future: balance of progress and responsibility
- Examples of US Initiatives

The Atomic Energy Act

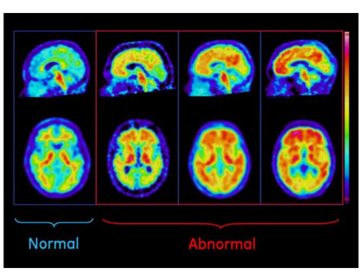
- The McMahon Act of 1946

  To conserve and restrict the use of atomic energy for the national defense, to prohibit its private exploitations, and to preserve the secret and confidential character of information concerning the use and application of atomic energy
- The USSR's first atomic bomb test – 1949
- Great Britain's nuclear test - 1952
- Policy of control by cooperation

Atoms for Peace

- 8 December 1953 - Dwight D. Eisenhower presentation to the General Assembly of the United Nations

  "The United States knows that if the fearful trend of atomic military build up can be reversed, this greatest of destructive forces can be developed into a great boon, for the benefit of all mankind."
- Establishment of International Atomic Energy Agency (IAEA)



Medical Diagnostics

Brain scan
Well logging sources Am 241/Be, 3-20 Ci
Nuclear power plant

Three Mile Island, PA

High expectations generated by the discoveries and diverse uses of nuclear technology

- The US ratified the Statute of IAEA on 29 July 1957

  "In fact, we did no more than crystallize a hope that was developing in many minds in many places … the splitting of the atom may lead to the unifying of the entire divided world."
  President Eisenhower

- IAEA mandate is to work with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies

  "The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose."

- Vienna, Austria – headquarters
  Two regional offices: Toronto, Canada (1979) and Tokyo, Japan (1984)
  Two liaison offices: New York City, US (since 1957) and Geneva, Switzerland (1965)
  Laboratories in Vienna and Seibersdorf, Austria (1961) and Monaco (1961)

Treaty on the Non-Proliferation of Nuclear Weapons (NPT)

- Entered into force: 5 March 1970

  The parties of the Treaty affirmed that *the benefits of peaceful applications of nuclear technology, including any technological by-products which may be derived by nuclear-weapon States from the development of nuclear explosive devices, should be available for peaceful purposes to all Parties to the Treaty, whether nuclear-weapon or non-nuclear-weapon States*

  Each nuclear-weapon State Party to the Treaty undertakes not to transfer to any recipient whatsoever nuclear weapons or other nuclear explosive devices or control over such weapons or explosive devices directly, or indirectly; and not in any way to assist, encourage, or induce any non-nuclear-weapon State to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices, or control over such weapons or explosive devices. (I)

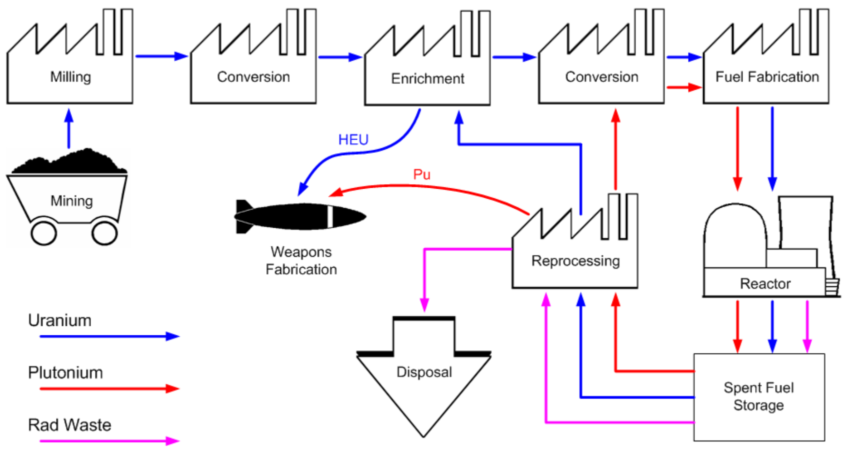
  Each non-nuclear-weapon State Party to the Treaty undertakes not to receive the transfer from any transferor whatsoever of nuclear weapons or other nuclear explosive devices or of control over such weapons or explosive devices directly, or indirectly; not to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices; and not to seek or receive any assistance in the manufacture of nuclear weapons or other nuclear explosive devices. (II)

  Each non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards (III)

- Five nuclear weapons state: China, France, Russia, UK and US

Civil Nuclear Energy and Proliferation (Dual-Use Dilemma)

- Reactors used to produce energy or for research produce plutonium that could be used in nuclear explosives
- The facilities used to enrich uranium or reprocess spent nuclear fuel can be used to produce material for nuclear weapons
- Undeclared or secret nuclear fuel cycle facilities could also be used



Fred Wehling, MIIS

Nuclear Safeguards

- Nuclear Safeguards are **measures to verify that States comply with their international obligations not to use nuclear materials** (plutonium, uranium and thorium) for nuclear explosives purposes
- Safeguards agreements with 175 States; about 100 of these states have small quantities protocols
  - Additional Protocol
  - Small Quantities Protocol
- 2018 Safeguards Implementation Report
  - 3,011 in-field verifications across the globe (vs. 2,843 in 2017), includes 183 complementary accesses (140 in 2017)
  - 1,314 nuclear facilities and locations outside facilities at which safeguards inspectors conduct

Lisbon Protocol: USSR nuclear arsenals in Russia, Ukraine, Belarus and Kazakhstan

- Belarus
- Ukraine
- Kazakhstan



Destruction of testing tunnels in Kazakhstan

Electromagnetic Isotope Separation (EMIS) Equipment found in Iraq

Iraq specialists manufactured some of the equipment in Iraq and some items were purchased.
They used the “Manhattan Project” Calutrons but with improvements: “Baghadtrons.”

(R. Wallace Proliferation Aspects of the Nuclear Fuel Cycle)

A.Q. Khan network acquired and sold nuclear components and technology

- The seizure of the cargo ship BBC China in October 2003, which had been transporting uranium enrichment equipment from a Khan network facility in Malaysia to Libya, publicly exposed both the network and Libya's nuclear ambitions.
- A.Q. Khan of Pakistan and his network provided nuclear technologies to Iran, Libya, possibly other states
  - 2003 - Iran admitted to IAEA that centrifuge components for U enrichment were acquired from Pakistan (per IAEA, P-1 centrifuge components and data of P-2 centrifuge)
  - 2003 – Libya disclosed information to IAEA on illicit supplies of fissile materials and nuclear technologies from Pakistan (per IAEA, centrifuge components, drawings of components)
  - 2003 – Pakistan acknowledged illegal transfers to other countries
  - 2004 – A.Q. Khan confessed on live TV about providing nuclear weapons technology to Iran, Libya and North Korea over the course of decades.
- At least 30 foreign companies and middlemen did deals with Khan; it was a global supply chain. Assistants/brokers based in Germany, Malaysia, S. Africa, Switzerland, Turkey, UK and UAE

(SIPRI report 2005, IAEA, Foreign Affairs 2018)

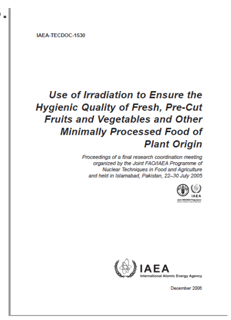
(R. Wallace Proliferation Aspects of the Nuclear Fuel Cycle)

Gas Centrifuge Components Recovered from the BBC China

Pres. Ahmadinejad tours Natanz Uranium Centrifuge Enrichment facility, Iran, 2008

Applications

- IAEA and FAO assisted Ethiopia in acquiring Co-60 sources to irradiate tsetse flies, which transmit sleeping sickness.
- Pineapples for export to the US are irradiated to increase their transportation/shelf life in Ghana. West Africa Trade Hub study concluded that irradiation may be the only means to increase agricultural exports from Africa.
- S. Africa was looking to use radioactive isotopes to combat poaching of rhinoceros.

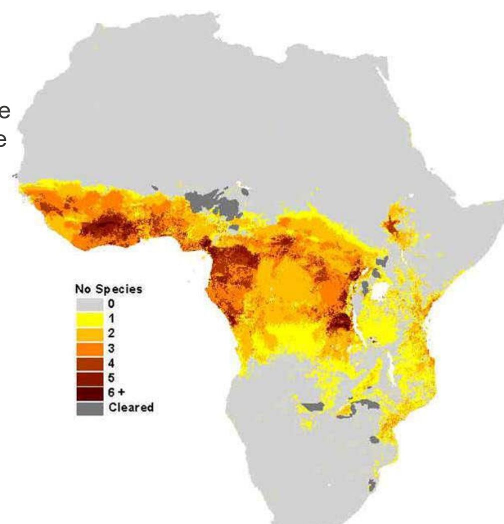


IAEA-TECDOC-1530

Use of Irradiation to Ensure the Hygienic Quality of Fresh, Pre-Cut Fruits and Vegetables and Other Minimally Processed Food of Plant Origin

IAEA

IAEA irradiation study, 2006



Tsetse distribution in Africa, FAO and DFID map, 1999

Abandoned sources

Goiania Incident, Brazil (1987) Cs-137, 1375 Ci

Abandoned medical devices (2006)

General underlying reasons for abandonment:

Lack of a disposal/end-of-life option

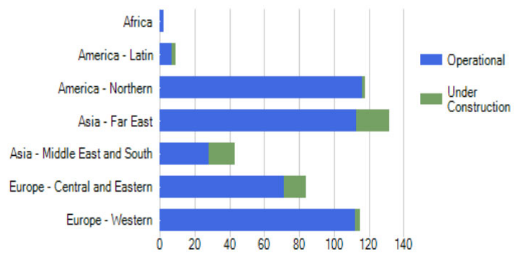
Expense of source disposal

Chernobyl (1986), Fukushima-Daichii (2011)

- Fukushima-Daichii incident 2011 thwarted "the nuclear renaissance"
  - Public opinion had been growing in favor of nuclear power prior to Fukushima event
  - Immediate after the incident: 2011 Ipsos Social Research Institute survey in 24 countries, WIN-Gallup International survey of 34,000 in 47 countries
- Media impact,
  - Study of 260 Belgian publications over 2 months & 1 year later – Fukushima is linked to Chernobyl, often articles started with Fukushima incident as an introduction, connection to major issues
- IAEA: Public acceptance of nuclear power reflects how perceived benefits compare with perceived risk
- Impact of Fukushima: change in policies
  - Abandoned nuclear power (Germany, Italy) or no longer interested (Kuwait)
  - Expressed doubts about nuclear energy (USA, France)
  - Continuation of the nuclear energy support (Russia, India, China) & newcomers (Belarus, UAE)

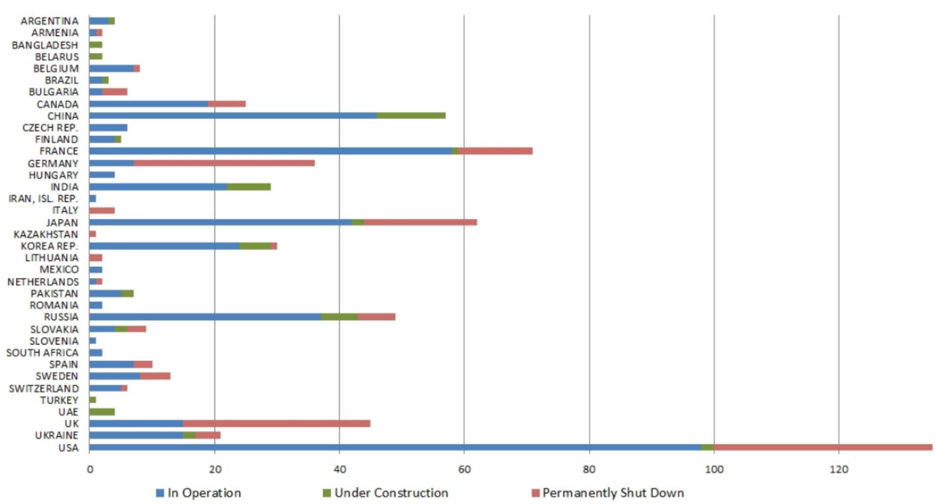
IAEA: Power Reactor Information System (PRIS)

- 449 Nuclear Power Reactors in operation
  397,650 MWe total net installed capacity
- 54 Nuclear Power Reactors under construction
  55,364 MWe total net installed capacity
- Regional Distribution of Nuclear Power Plants:

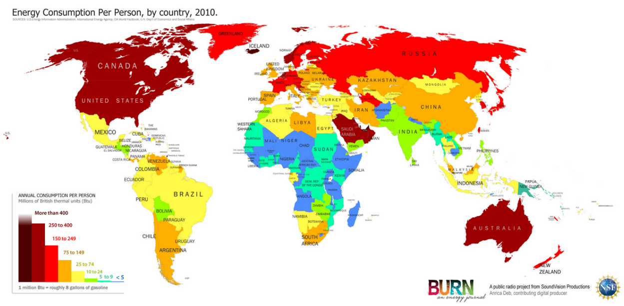


(https://pris.iaea.org/PRIS/home.aspx)

Number of Power Reactors by Country and Status



The Need for Stable Power

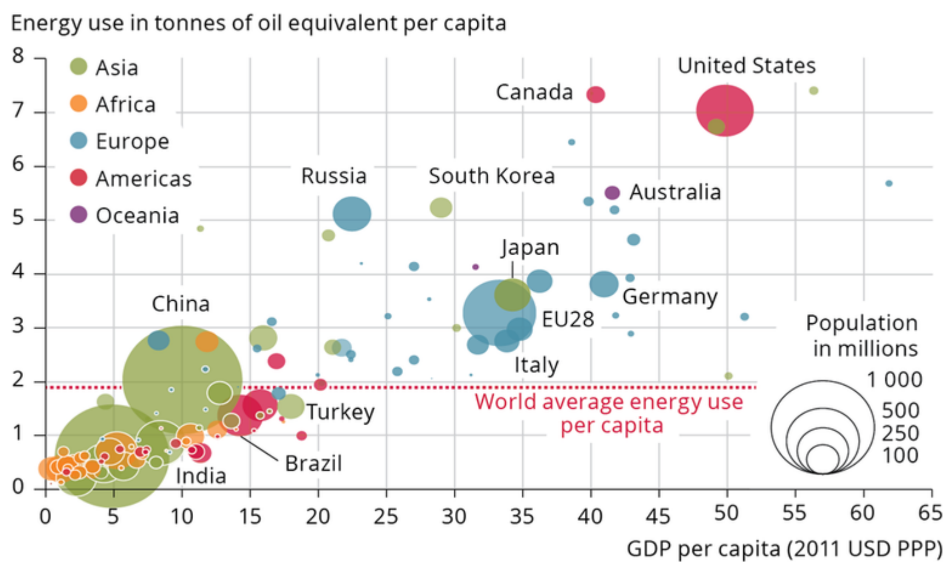


More than 3.5billion people live in the marked region.

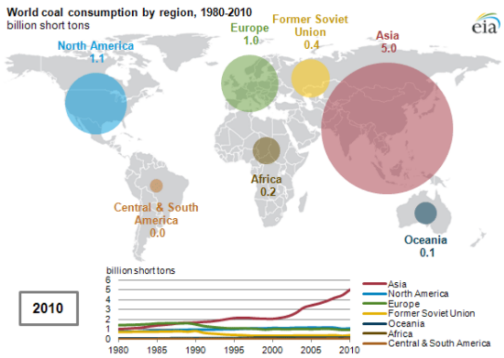
Kanpur, India has severe power problems.

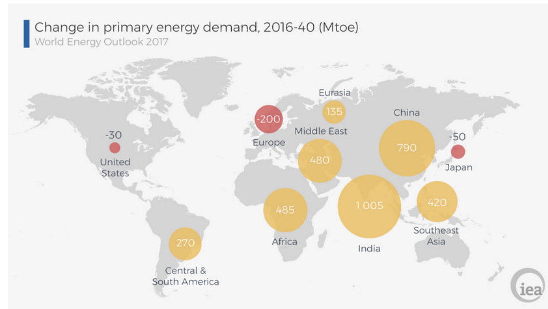
Loha Singh steals power for people and claims India's government failed to provide electricity to all.

Per capita energy consumption vs. per capita GDP, 2011



Burning coal to produce electricity





Growth of regional coal consumption
percent change from 1980 to 2010

World	94%
Asia	403%
North America	50%
Europe	-32%
Former Soviet Union	-42%
Africa	92%
Oceania	96%
Central & South America	156%

Share of global coal consumption
percent of total world consumption, 1980 and 2010

	1980	2010
Asia	24.3%	63.1%
North America	18.2%	14.0%
Europe	34.2%	12.0%
Former Soviet Union	18.2%	5.5%
Africa	2.7%	2.7%
Oceania	1.8%	1.9%
Central & South America	0.5%	0.6%

Nuclear safety and security framework

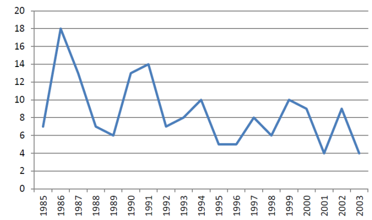
NSG Nuclear Suppliers Group
(1974)

- NPT (1970)
- Safeguards or Small Quantity
  - Additional Protocol
- Convention on the Physical Protection of Nuclear Materials (CPPNM) (1987)
  - Strengthening the Convention on the Physical Protection of Nuclear Materials and Nuclear Facilities (2005)
- Convention on Nuclear Safety (1996)
- UN Security Resolution 1540 (2004)
- International Convention for the Suppression of Acts of Nuclear Terrorism (ICSANT) (2007)
- Information Circular 908 (INFCIRC/908): A Global Tool for Mitigating Insider Threats (2016)
- Nuclear Security Summits (2010, 2012, 2014, 2016)

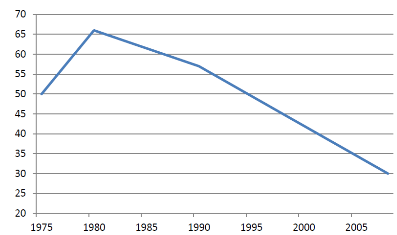
Code of Conduct on the Safety and Security of Radioactive Sources (2001, 2003)

1978 NNPA, loss of interest

- The 1978 Nuclear Nonproliferation Act (NNPA)
- The interest to nuclear energy generation, technologies, applications and research is waning in the US and other developed countries whereas other countries promote studies of new nuclear-based technologies
- Research career options and education opportunities have diminished in the US
- Renewable energy



Graduation rates of radiochemistry Ph.D.'s for 1985-2003

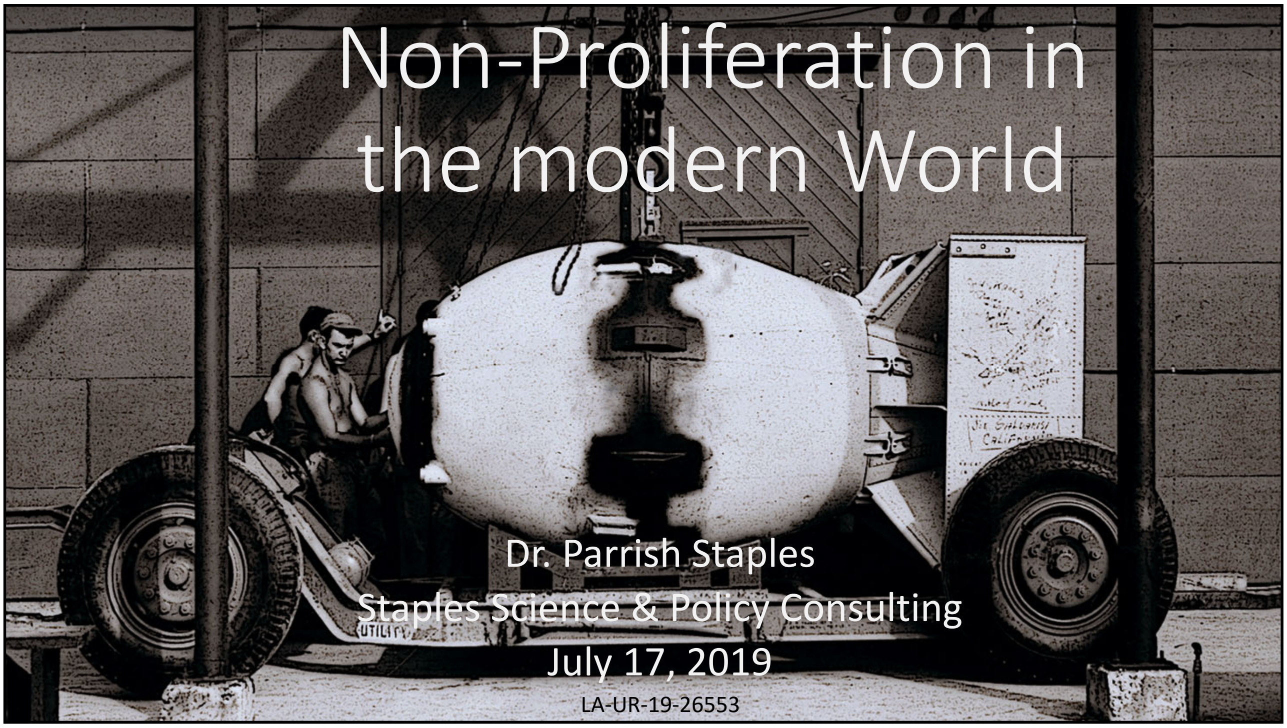


Number of nuclear engineering programs in the US

Looking into the future

- How to balance progress with responsibilities?
- Will US remain a leader in non-proliferation efforts?
- How to train new cadre of professionals? How to stay current in research?

Nonproliferation regime has had its ups and downs and there will be new challenges ahead. We need to be proactive and prepared.



Nonproliferation – Highly Enriched Uranium (HEU) minimization & Global Nuclear Threat Reduction

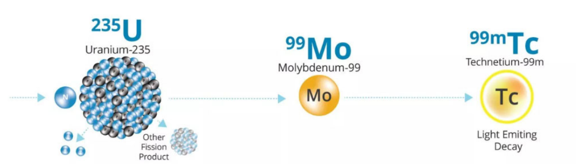
- 1990's forward
  - Interesting and challenging efforts to quantify/stabilize/secure post USSR nuclear materials and facilities
  - Significant collaborative efforts with the IAEA throughout the 90's
  - U.S. HEU minimization effort as well as a number of the most difficult international NP programs
- RERTR, (1978), a HEU minimization effort: technology & policy alignment – the laws and regulations that supported the programs and the technologies that supported the policies.
  - Policies
    - Federal Register / Vol. 51, No. 37 / Tuesday, February 25, 1986 / Rules and Regulations, NUCLEAR REGULATORY COMMISSION, 10 CFR Part 50, Limiting the Use of Highly Enriched Uranium in Domestically Licensed Research and Test Reactors
    - "Schumer Amendment" to the Energy Policy Act of 1992, specifies additional conditions that must be met before highly-enriched uranium (HEU) can be exported from the United States
    - American Medical Isotopes Production Act of 2012
  - Conversion
    - Regulatory approval, safety and operational analysis
  - Fuel Development
    - Existing fuel as well as new fuels (impacts to next generation/SMR etc)
  - Medical Isotope Production
- Repatriation support for both U.S. and Russian HEU
  - January 31, 2012, DOE issued the Revised Fee Policy for Acceptance of Foreign Research Reactor Spent Nuclear Fuel From High-Income Economy Countries.

9/11

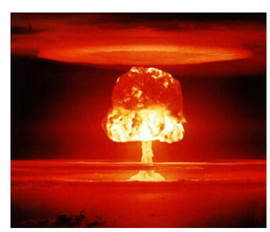
- Significantly accelerated nuclear security efforts and culminated in the formation of the DOE/NNSA Global Threat Reduction Initiative "GTRI", now managed as the Offices of Material Minimization and Management, and Global Material Security.
  - GTRI had 3 regional offices, each with a global technical focus
    - NA/SA (Radiological)
    - EU/Africa (HEU conversion)
    - FSU/Asia (Removal)
  - Domestic as well as international efforts
    - Address concerns as well as demonstrate leadership

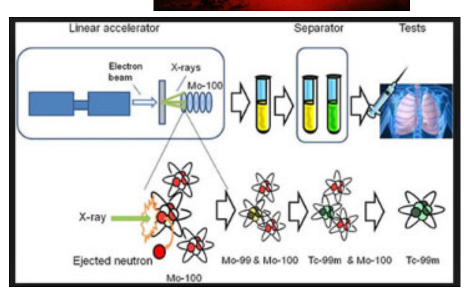
- Overview of two significant efforts within the Threat Reduction portfolio that carry over into current events that are intertwined in international business, politics, safeguards, security…
  - Mo-99 - "Stress/Rest test"
  - MNSR – "Miniature Neutron Source Reactor"

Mo-99



- ~80-100k patients daily (globally) are diagnosed for heart disease with a "stress/rest" test
- Shortages in ~2005-2007 got the attention of doctors, who got the attention of congressman, who got attention of the White House, who asked questions
- National Security justification
- U.S. effort was coordinated thru the WH Office of Science and Technology Policy (OSTP), with the National Security Council (NSC) as well as broad interagency support. e.g. the Veterans Administration (VA) supported the effort by making a policy to preferentially procure non-HEU based Mo-99 and Centers for Medicare and Medicaid Services (CMS) developed a policy to pay a $10 per dose premium for non-HEU based Mo-99
- Reluctance from industry to convert, cost, market share and acceptance (change averse)
- Canada was a main supplier with aspirations of global dominance
  - Main suppliers were/are
    - Nordion/AECL (Canada), now out of the business
    - Curium (Mallikrodt, Covidien), (The Netherlands), converted to LEU 2017
    - IRE (Belgium) in process of converting to LEU
    - Necsa/NTP, first major producer to CONVERT to LEU Medical Isotope production in 2010
    - ANSTO (Australia) LEU
    - NorthStar Medical Radioisotopes, (USA), 2018 FDA approval
    - Russia, Argentina, provide some domestic supply

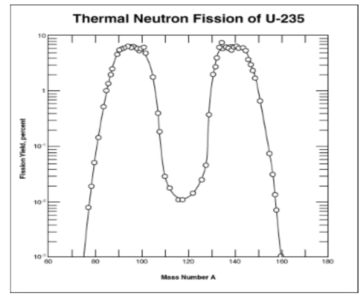


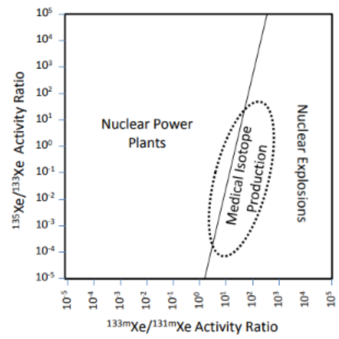


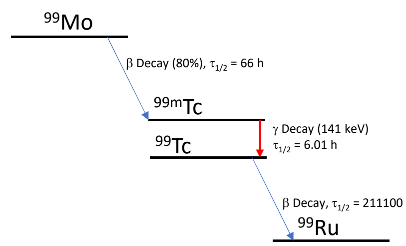
Implications in NP & TR

- ~$2B/yr in global business?
  - U for manufacture of targets
  - Targets are transported for irradiation,
  - Irradiation takes 5-7 days
  - Mo-99 suppliers (~$200M/yr in business)
  - Technetium generator suppliers
  - Tc-99m suppliers
  - End users –SPECT

- It’s not just the HEU…
  - Short irradiation time U targets
    - Zenon signature mimics testing
  - Pu recovery chemistry



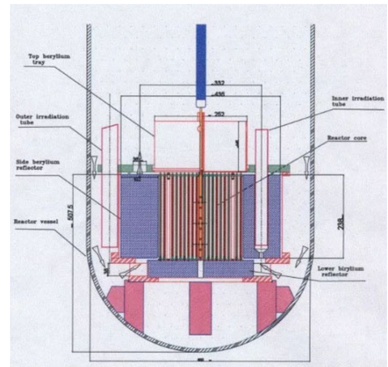




Will it ever be resolved?

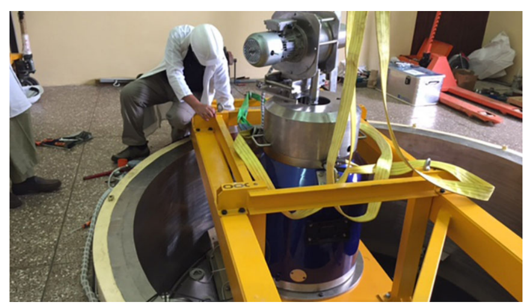
- OECD/NEA HLGMR forum, NAS studies
  - International business and trade – always an issue
  - States rights to technologies, new producers – always an issue
  - Patients rights to health care – always an issue
  - HEU to LEU conversion – almost complete
  - U.S. domestic production – starting to ramp up

Conversion of MNSRs



- China, Ghana, Iran, Nigeria, Pakistan, & Syria as well as the U.S. and IAEA participants
- Coordinated Research Project (CRP)
- Why mention Canada and Jamaica…
  - SLOWPOKE's (Safe LOW-POwer Kritical Experiment)
- What is an MNSR, 30 kW reactor, ~ 1 kg core of HEU (90%)
- Development of mutual understanding via IAEA meetings of objectives/process
  - Minimizing the civilian use of HEU
  - Forum for cooperation among participants

MNSR Conversion Status



- MNSR IAE, operated by the China Institute of Atomic Energy in Beijing, first reached criticality in 1984. The 2016 conversion was a result of a cooperative project between China Atomic Energy Authority (CAEA) and U.S. Department of Energy.
- Ghana's Chinese-origin MNSR conversion in 2017, is the first reactor of this type to be converted outside of China, establishing this cooperative effort as a model for similar cooperation on future MNSR conversions.
- With the conversion to LEU fuel and removal of highly enriched uranium (HEU) fuel from Nigeria's research reactor in early 2018, all 11 operational research reactors in Africa are now running on low enriched uranium (LEU).

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